VI. THE SEISMICITY OF THE EARTH

6.1 The main seismic zones

Each year the United States seismological service determines the hypocentral co-ordinates of about 5,000 earthquakes. The location of the epicentres of these earthquakes has made it possible to provide a picture of the earth's seismic zones which, combined with measurements of the positive and negative magnetic anomalies alternating on either side of the axis of ocean ridges, has led to the theory of océan-floor spreading and a description of the main features of the earth's structure. This new "global tectonics" has, in turn, led to a better understanding of the causes and mechanism of earthquakes.

World maps remain very similar from year to year: the strongest seismic activity always occurs in the same regions. However, differences may be observed regionally or locally, as new foci rarely occur in exactly the same places as the old ones. Occasionally, earthquakes occur in areas where they are unusual: the earthquake of 29 March 1954, at a depth of 630 km beneath the Sierra Nevada in Spain, is a classic example.

The map of the epicentre of the 700 strongest earthquakes - or those most interesting because of their location- which occurred in 1971 (fig. 6-1) clearly shows the main seismic zones of the world:

6.1.1 The circum-Pacific seismic belt, where 80 per cent of total seismic energy is released, is marked out by the arc of the Aleutian Islands, Kamchatka, the Kurile Islands chain and the east coasts of the Japanese Islands. The seismic zone then divides into two branches,

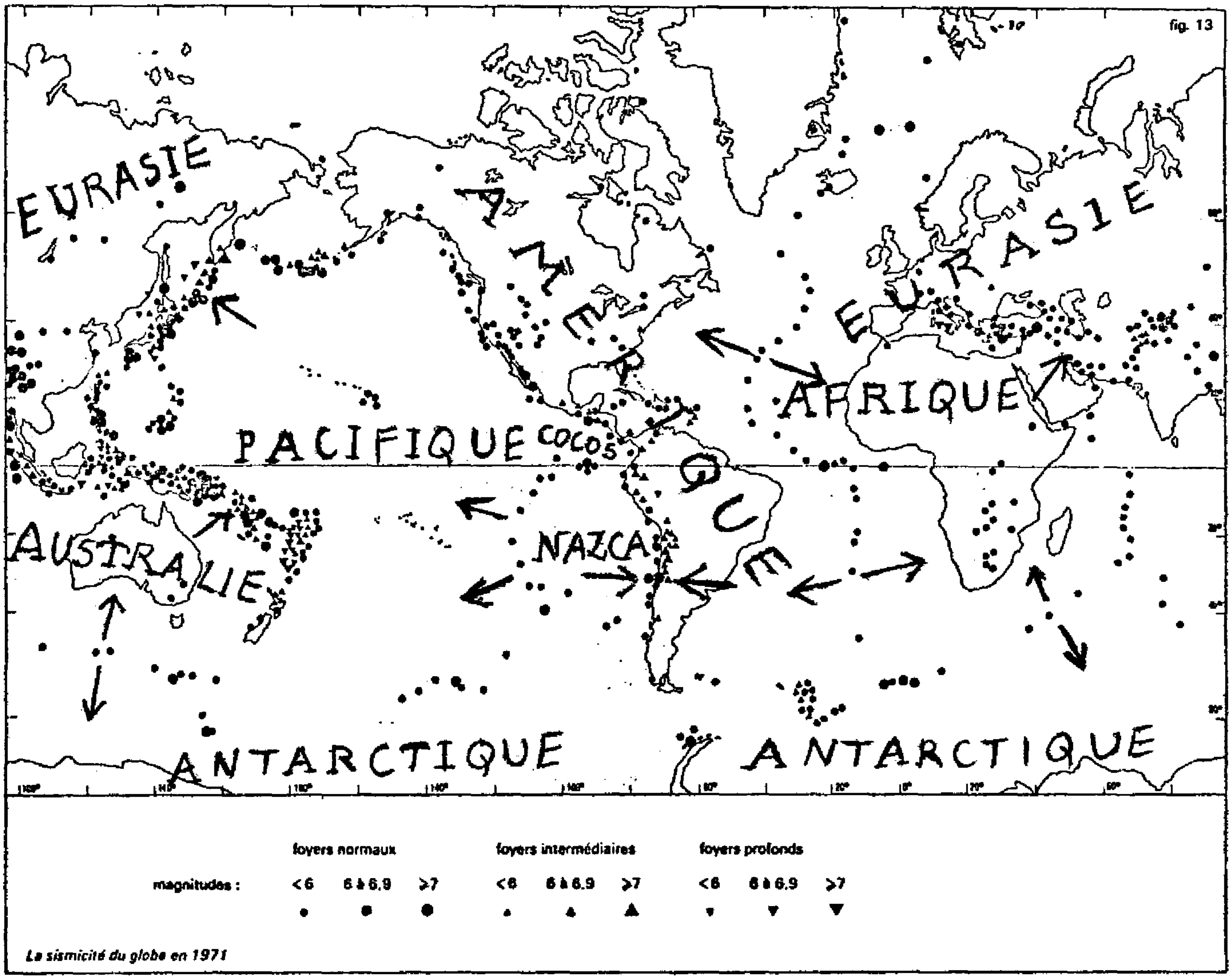

Fig. 6-1 : The seismicity of the globe and the major tectonic plates. Main epicentres in 1971. (J.P. Rothé, UNESCO, 1971 Annual Summary).

one passing through Taiwan and the arc of the Philippines, and the other, further east, following the submarine ridge formed by the Bonin and Marianas Islands, Guam and the western Caroline Islands. The two branches meet in New Guinea and the belt continues through the Solomon Islands, the New Hebrides, Fiji, Tonga, Kermadec and New Zealand. Throughout this zone, "intermediate" foci (at depths of 70 to 300 km) and "deep" foci (at depths of 301 to 725 km) occur together with normal foci (less than 70 km deep) on inclined planes (Benioff planes) which dip away from the Pacific, except in the New Hebrides region.

In the southwest Pacific, the seismic zone is of a different character: it is associated with an oceanic rift which runs from the Balleny Islands in Antartica to the Gulf of California, passing through the ridge of Easter Island and the Galapagos Islands. Earthquakes in this zone are all of normal depth.

Another zone begins in the southern Antilles, runs along the Pacific coast of South America and under the Andes (where intermediate and deep earthquakes are again associated with normal earthquakes), takes in the Antilles loop and extends through Mexico, California and Alaska, closing the circle at the Aleutian Islands.

6.1.2 The Transasiatic seismic zone covers the whole of the Alpine orogenic system, from Spain and North Africa to the mountain ranges of Central Asia; passing through Burma and Indonesia it joins the circum-Pacific belt in the Banda Sea.

6.1.3 The mid-oceanic rifts (Indo-Atlantic and Indo-Antarctic), long fracture lines which divide the Atlantic Ocean and the Indian Ocean into two parts, are the site of frequent earthquakes which are all shallow and generally of moderate magnitude.

The authors of "plate tectonics" envisage a number of blocks or lithospheric plates whose boundaries coincide with the narrow active seismic zones: Eurasia, Africa, Australia, the Philippine sea plate, the inner Pacific, the Nazca plate, the Cocos plate and Antarctica. The strong lithospheric plates, which are about 100 km thick, have an upper crust which is granitic under the continents and "oceanic" (basalt) under the sea; they rest on a layer capable of slow flow, called the asthenosphere, a zone of weakness which behaves like an imperfectly elastic body and absorbs seismic waves.

As a result of convective movement of thermal origin, the deep magma rises along the rifts of the oceanic ridges, forcing the plates to move away from the ridges and, consequently, to collide with neighbouring plates. These collisions build up stresses which are released as earthquakes, together with the formation of mountain ranges. The violence of the collision between two plates depends on whether they run straight into each other, whether they are moving more or less obliquely or whether one of them is stationary. A denser plate (oceanic) made of basalt and peridotite meeting a lighter plate (continental) will thrust under it into the earth's upper mantle. This explains the distribution of foci along the "Benioff planes" round the periphery of the Pacific and, in particular, all along South America (fig. 6-2).

In the tension areas along the rifts of the ridges, the energy released in the shocks which accompany the separation of two plates is less than that released in the compression areas where two plates meet. Seismic activity is concentrated in the narrow zone of the rifts, the foci are all shallow and confined to the lithosphere, and no earthquakes of great magnitude are observed.

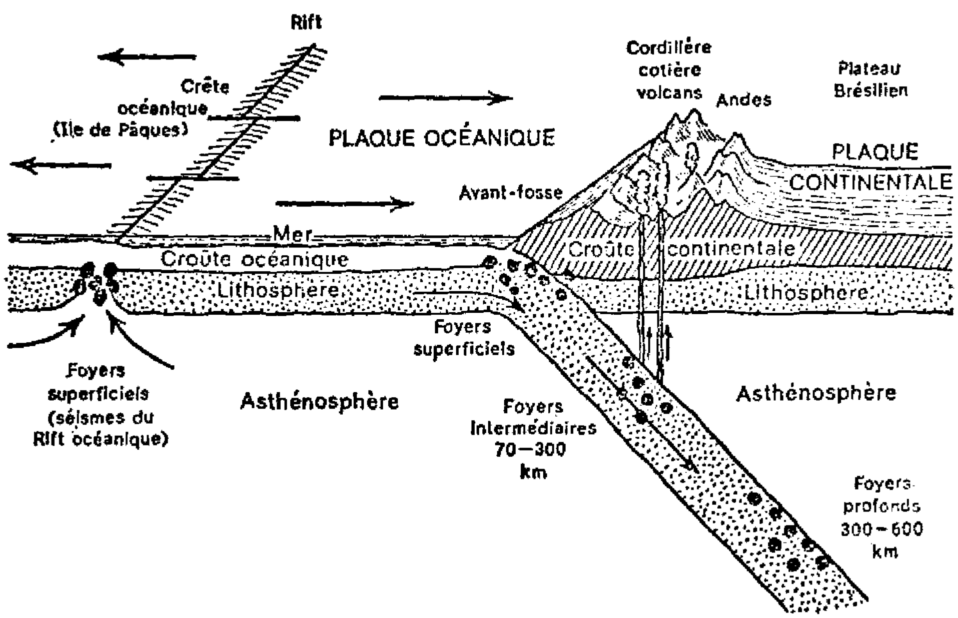

Fig. 6-2 : Cross-section of the southeast Pacific zone.
(J.P. Rothé, Séismes et volcans, Que sais-je ?,1972)

The tectonics, which are relatively simple in the Pacific and along the ridges, are much more complex in the more tortuous Alpine zone, where the part played by the Mediterranean, whose structure is largely of the Pacific type, is still not well known. In the Alpine zone, seismic activity coincides with the main mountain ranges and is stronger where the folds are more recent. It also occurs along a few large "transcurrent" faults, such as the North Anatolian fault and the Zagros fault. These faults are characterized by horizontal shearing movements, in which the relative displacement of the two sides - righthand or lefthand - may reach as much as several metres in a single earthquake.

VII. EARTHQUAKE PREDICTION

The study of regional seismicity and the outline of seismic zones make it possible, within the framework of global tectonics, to predict the regions in which earthquakes will occur; the real problem in prediction is to be able to specify in advance the exact place, date (as precisely as possible) and magnitude of a future earthquake. It is only a short time since a strictly scientific approach has been applied to the short-term prediction of earthquakes, and the first successes recently achieved by certain research workers give reason to hope that such forecasting will be possible in the fairly near future. It would then be possible, thanks to two kinds of prediction, to adopt a preventive strategy which might greatly reduce human and material losses.

Long-term predictions could be used:

- for strengthening the structures of existing buildings;
- for including local authorities to issue new regulations on building and land use and, in particular, for improving the choice of sites for new human settlements;
- for launching campaigns to inform and educate the population on safety rules and general preventive measures;
- for drawing up relief plans.

Short term predictions, on the other hand, would make it possible:

- to mobilize relief in the event of a disaster;
- to set up procedures for evacuating endangered buildings and dangerous areas (fire risk);
- to shut down certain dangerous industries (nuclear reactors, electric power stations, oil and gas pipelines, etc);
- to evacuate low lying coastal areas liable to be swept by tsunamis.

7.1 Regional prediction (long-term)

Regional prediction has been the subject of recent works, the titles of which are significant:

> Seismicity as a guide to global tectonics and earthquake predictions, by L.R. Sykes (Tectonophysics, vol. 13, 1972, pp. 393-414).

> Possible criteria for predicting earthquake locations and their application to measure plate boundaries of the Pacific and Caribbean, by J. Kelleher, L. Sykes and J. Oliver (Journal of Geographical Research, vol. 78, No. 14, 1973, pp. 2547-2585).

Systematic study of the distribution of the epicentres of major earthquakes and of their aftershock zones along the boundary between the Pacific and American plates shows that the zones of activity migrate from east to west along the Aleutian arc and from north to south along the coasts of Chile. Between the zones of recent activity there are quiet regions. The map in fig. 7-1 shows a characteristic example in central America: the six quiet zones ("gaps") have not had an earthquake for 45 years or more.

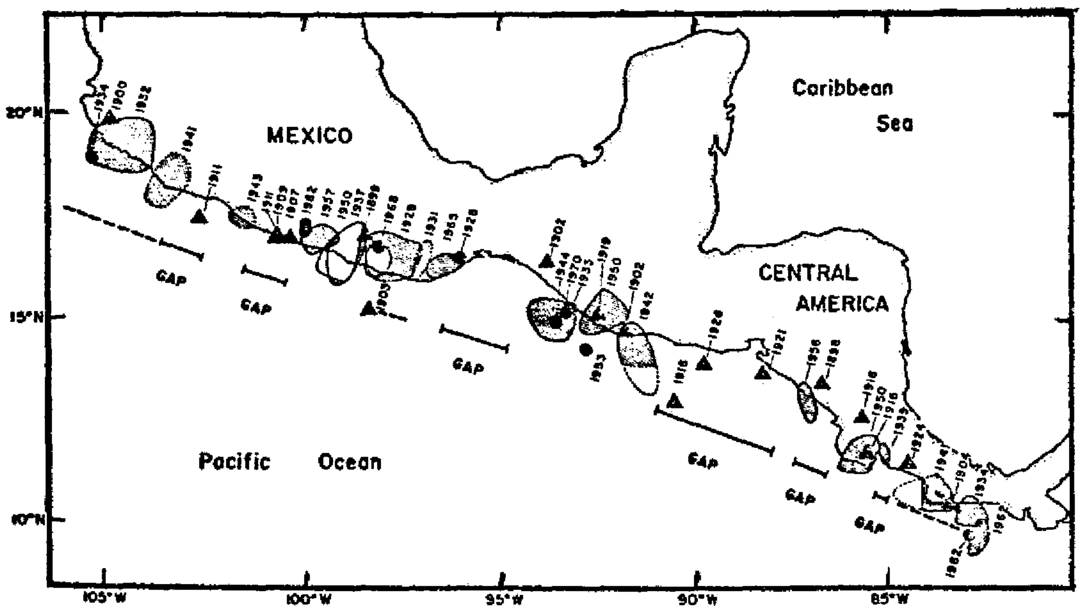

Fig. 7-1 : Rupture zones and epicentres in Central America in the twentieth century. The shaded areas are rupture zones since 1928; the triangles and circles show the epicentres of earthquakes which occurred before and after 1928, respectively. Note the six gaps in which there has been no rupture for 45 years or more, and the three areas which last ruptured between 30 and 45 years ago.

These recent studies show that major destructive earthquakes do not recur in the same place along faults until several decades or more have elapsed - the time needed for sufficient stress to build up. In the main seismic regions, it is the present quiet zones which present the greatest danger of future earthquakes. In these quiet zones, seismic activity is very slight and not even micro-shocks are observed. It is not yet known whether the quiet zones will become more active for years, weeks or days before major earthquakes occur again. Monitoring these zones by the various geophysical methods available therefore seems to be one of the tasks now incumbent on seismologists. It can be seen, however, that for the time being "prediction" is limited to relatively large areas in which earthquakes are liable to occur within a period that it is not yet possible to determine. The problem is probably simpler along the "circum-Pacific belt", where the plate tectonics are clearer. The regions with large transcurrent faults are also interesting: regular east to west movements of seismic centres and rupture zones, which are often hundreds of kilometres long, are known to have occurred along the North Anatolian fault between 1939 and 1953. After that date, the movement was reversed, but the regularity of the process was less distinct.

Finally, it must be emphasized that the occurrence of destructive earthquakes within tectonic plates, mainly in Eurasia or Africa, defies the simple explanation provided by the theory of plate tectonics along the circum-Pacific belt, since the effects of the meeting of two continental plates (Eurasia and Africa) in the Alpine and Himalayan regions seem to be particularly complex.

7.2 Short-term prediction

The most remarkable case of prediction is that relating to the Haicheng area in China (1975). The people were evacuated 5 ½ hours before the heaviest shocks (magnitude 7.3), thus avoiding considerable loss of life (90 per cent of the houses were destroyed). Similarly, in the province of Yunan (May 1976) two earthquakes of magnitude 7.6 and 7.5 were predicted, which made it possible to give the alarm 8 minutes before the first shock, to evacuate the population and shut down dangerous industries (electricity generation, etc.). These predictions were based on observation of the water level in deep wells, the presence of radioactive gas (radon) in the water, foreshocks and the unusual behaviour of animals.

In the United States of America several earthquakes have been predicted, in particular in California (November 1974), but their lesser magnitude (5) did not justify large movements of population, as was the case in China.

7.2.1 Research programmes

Extensive programmes of research have been proposed in several countries, including Japan, the United States of America, the Soviet Union and China. These programmes are based mainly on the recording and study of the occurrence and variation of geophysical phenomena:

* Dilatation: when a rock is subjected to stress, it may be deformed or even broken. Just before rupture there is a non-elastic increase in volume, caused by the opening and extension of fissures in the rock. This phenomenon occurs when the stresses are equal to about half the breaking load. Dilatation is accompanied by substantial changes in specific resistance, and in the velocity of seismic waves (change in the ratio $\frac{Vp}{Vs}$).

* Seismic regions undergo a very large number of small shocks constituting the "background noise". It often happens that major shocks are preceded by a period of quiet, during which the background noise decreases, reaches a minimum value and then increases abruptly just before the main shock.

* Three or four months before a strong shock, the compression stresses tend to be aligned in the same direction as those of the coming earthquake.

* In the zone of the seismic focus, the rocks of the earth's crust undergo abnormal changes in volume, which are reflected in variations in elevation.

* The pre-monitory phenomena are often accompanied by changes in the level, turbidity and temperature of the water in deep wells. These changes are often associated with an increase in the amount of radioactive gas: radon.

* Variations in the earth's magnetic field can also be detected by the use of magnetometers.

7.2.2 Physical models

Although the prediction of earthquakes can be based solely on empirical observations, the construction of physical models makes it possible not only to have greater confidence in the predictions, but also to direct research programmes in a much more coherent manner.

Two models have been proposed :"The theory of dilatation and diffusion" developed by Amos N. Nut in 1972 and revised by C.H. Scholz, L.R. Sykes and Y.P. Aggarwal in the United States in 1973; and "The theory of dilatation and instability" proposed by the Earth Physics Institute of Moscow in 1971. These two models have a common starting point: dilatation, or the development of fissures associated with the increase of stresses preceding an earthquake.

It is only at a second stage that the open fissures cause a change in the physical properties of the rocks, thus marking the onset of the precursory symptoms. The ratio $\frac{Vp}{Vs}$ decreases, the specific resistance increases or decreases, depending on whether the rock is saturated with water or not (by passing through the fissures, this water may leach the rock and thus take up radon). At this stage, according to the American model, the number of small shocks decreases; this is due to the increasing number of fissures which can no longer be saturated with water. As a result, friction increases, thus diminishing fracturing.

At the third stage, on the other hand, the two models present notable differences. According to the American model, the water diffuses in the under-saturated zone subject to dilatation. This has the effect of increasing the velocity of seismic waves and raising the interstitial pressure in the fissures, thus creating an additional stress which sets off the main shock.

According to the Russian model, water does not intervene at this third stage. On the other hand, the accelerated increase in the number of fissures leads to instability and rapid deformation at the level of the main fault. The stresses decrease partially in the deformation zone, the fissures tend to close again and the rock recovers part of its initial physical properties. This sequence takes account of the increase in the speed of seismic waves, the decrease in volume and other changes usually observed at the third stage. The increase in instability finally leads to fracturing which sets off the main shock.

The duration of the premonitory phenomena can be related to the magnitude of the expected earthquake by an empirical formula (J.H. Whitcomb, J.D. Garmany and D.L. Anderson). An earthquake of magnitude 5 is preceded by premonitory phenomena extending over four months, whereas a much stronger earthquake (magnitude 7) is announced more than 14 years in advance by such anomalies. This formula, although approximate (particularly with reference to large magnitude) makes it possible to predict earthquakes a decade in advance.

In the present state of work, the small number of predictions made does not yet justify outright rejection of methods which do not show good reliability. Consequently, it is not yet possible to establish a really operational system of prediction.

In view of the results already obtained, the Commission on Earthquake Prediction of the International Association of Seismology and Physics of the Earth's Interior, meeting at Tashkent in May 1974, made a number of recommendations intended to facilitate exchanges of information and encourage research in individual countries. Experts on prediction could thus be made available to countries intending to develop a research programme.

Some seismologists, however, do not share the optimism of their colleagues. Lomnitz (1973) in his recent work "Global Tectonics and Earthquake Risk" asks the question: "How important is it actually to predict earthquakes ?" and he goes on to say : "Indeed, if the great

1964 Alaska earthquake could have been predicted, about 100 people killed in that disaster might be alive today; but perhaps twice as many might be dead as a consequence of traffic disruptions and other dislocations caused by the prediction itself. As for damage, it would be difficult to show how a warning could have made much of a difference, even if it had come a week or two in advance of the earthquake. Any savings due to preventive measures would have been offset by the economic consequences of an evacuation of cities and coastal towns".

... And what would happen if the prediction did not come true ?

VIII. EARTHQUAKE PROTECTION

8.1 Introduction

Since they are unable to predict or prevent earthquake, scientists, engineers and architects have tried to limit the damage they cause. In addition to protection of housing, increasingly frequent attempts are now being made to protect industrial buildings whose destruction by an earthquake would constitute a particularly grave danger: chemical factories, thermal power stations, stocks of toxic or petroleum products, dams and, especially, nuclear power stations. Defence against earthquakes relies, first, on evaluation of the seismic risk, which means making maps of seismic zones, and secondly, on strict application in those zones, both of the earthquake protection rules contained in building codes, and of land use legislation (land development, zoning, etc.).

8.2 General programme of seismic map-making

The UNESCO Working Group on Seismic and Seismotectonic Maps has adopted a number of detailed recommendations which are summarized below.

8.2.1 Use of a single intensity scale

It is desirable that use of the MSK intensity scale described above, a detailed scale which is easy to apply in any region, should be generally adopted.

The following conversion table for the different seismic scales was compiled by Medvedev, Sponheuer and Karnik :

MSK seismic scale 1964	Scale of the USSR Academy of Sciences' Institute of Geophysics 1952	Modified Mercalli scale (MM) 1931	Japanese scale 1950	Rossi-Forel scale 1873	Mercalli-Cancani-Sieberg European scale 1917
1	1	1	0	1	1
2	2	2	1	2	2
3	3	3	2	3	3
4	4	4	2-3	4	4
5	5	5	3	5-6	5
6	6	6	4	7	6
7	7	7	4-5	8	7
8	8	8	5	9	8
9	9	9	5-6	10	9
10	10	10	6	10	10
11	11	11	7	10	11
12	12	12	7	10	12

8.2.2 National catalogues of epicentres

Catalogues of earthquakes provide the original basic data for making maps of seismic activity.

For each earthquake the catalogues should include information on the date and time (as precise as possible); epicentre co-ordinates, stating degree of accuracy; maximum intensity; focal depth, based on macroseismic data (showing the formulae used for calculating the depth); magnitude, based on macroseismic observations (with the conversion formula used); the radii of the degree V isoseismal and of the isoseismal marking the boundary of the macroseismic area.

In the case of recent earthquakes, the foregoing information should be supplemented by data calculated from instrument readings: epicentral co-ordinates, depth, magnitude.

In countries which have a long written history, the collection of all available information on old earthquakes should be encouraged. This is really a historian's work, which requires, in particular, a knowledge of ancient languages. Such research can lead to valuable results. One example is the study made by Ambraseys of earthquakes in Anatolia between the years 10 and 1100. 1/

The historical data collected made it possible to draw a map showing the Anatolian settlements which were destroyed one or more times during the period. The map reveals three relatively narrow and particularly dangerous tectonic lines. These researches also show that along the tectonic lines observed, destructive earthquakes followed each other in quick succession during a short period which was preceded and followed by calm periods of 75 to 150 years.

8.2.3 Maps of epicentres

These maps are drawn on the basis of catalogues prepared according to the above recommendations. The data shown on them should be homogeneous for the whole region covered by the map; the period considered, which should be as long as possible, will depend on the value and extent of the information contained in the catalogues.

In countries with high seismicity, the instrumental period (starting in 1901) may be used as a reference period: the map of

1/ N.N. Ambraseys, Early Earthquakes in the Near and Middle East, UNESCO Report, SC/1473/69.

epicentres of the Balkan region (UNDP/UNESCO Survey of Seismicity of the Balkan Region, 1973) gives, with the aid of special symbols, the following information for each epicentre: accuracy of determination of the epicentre (δ EP $\leqslant 0^{\circ}3$; $\leqslant \pm 1^{\circ}$; $\leqslant \pm 3^{\circ}$), magnitude and accuracy of determination of magnitude (δ M $\leqslant \pm 0{,}3$; $\leqslant \pm 0{,}5$; $\leqslant \pm 1$), focal depth in km (1 - 5; 6 - 10; 11 - 20; 21 - 40; $>$ 40 for normal earthquakes; $<$ 90; 91 - 130; 131 - 200 for intermediate earthquakes) and accuracy of determination of the depth (δh : $\frac{h}{1{,}5}$ to 1,5 h; $\frac{h}{2}$ to 2 h; $\frac{h}{3}$ to 3 h).

Epicentre maps covering longer periods may also be made, using both macroseismic and instrumental data; the accuracy of the determination of the epicentre can be indicated by special symbols, and the maximum intensity at the epicentre may be taken as a basis for comparison between different earthquakes.

8.2.4 Maps of maximum observed intensity

These maps are essential working material for the study of seismicity, but they should not be assimilated to maps of seismicity or maps of seismic zones since their content depends on the period over which observations were made. It also depends on the population density of each region; in thinly populated countries the data are often incomplete.

By way of example, the 1/1,000,000 scale map of maximum observed intensities in the Balkan region (UNDP/UNESCO Survey) shows areas in which the maximum observed intensity during the period 1901 - 1970 reached VII, VIII, IX or X degrees (MCS); areas in which the intensity probably attained the same degrees during the period 1600 - 1900 are also shown.

8.2.5 Seismotectonic maps

Seismotectonic maps show the main tectonic features in relation to the seismicity indicated by the preceding maps; their final purpose is to delimit seismic zones which are as narrow as possible in relation to the zones of contemporary and older tectonic movements: tracing the lines of major dislocations and secondary fractures is a task of prime importance. Attempts are now being made to use satellite photo-mosaic assemblies to identify the major fault lines, only some sections of which have so far been detected on the ground, and to determine their seismogenic role. Other tectonic data must also be taken into consideration: the history of the horizontal and vertical movements of the earth's crust; the direction, speed and differentiation of these movements; and the different types of fold.

Neotectonic research, which is unfortunately not yet very far advanced, should provide valuable aid in making the seismotectonic map more accurate; it relies on a combination of geodesic methods (levelling, triangulation) and morphological methods (e.g. study of elbows in rivers, line of recent faults, etc.).

It is highly desirable that precision levelling be carried out periodically along contour lines passing through regions which are of interest as regards their seismicity; one example of such work is the Franco-German collaboration on two contour lines from the Vosges to the Black Forest across the Rhine Valley. In a few years time it should thus be possible to measure the extent of neo-tectonic movements.

Some writers also make use of other geophysical data: variation in depth of the Mohorovicic discontinuity determined by deep seismic sounding; maps of gravimetric and magnetic abnormalities, etc.

8.3 Recommendations for improving earthquake protection

The foregoing account shows that the improvement of earthquake protection must be based, first, on an improvement of national networks of seismological stations permitting closer examination of regional seismicity, and hence more reliable supply lines for danger zones and, secondly, on general application of earthquake protection codes.

8.3.1 Improvement of the network of seismological stations

A number of countries situated in or near seismic zones still have no seismological stations or only operate a single station.

Every national seismological network should comprise at least four stations. The basic instrument should be a vertical component seismograph with a natural period of about 1 second and a magnification ranging from 1,500 to several tens of thousands; each station should also have a high quality recording drum, and there should be a device ensuring synchronization of the time scales for the whole network. At least one of the stations should be equipped with three instruments (two for horizontal components and one for the vertical component).

As a rough guide, the cost of installing a single-component station is of the order of $6,000 including the recording hut, and the cost of installing a three-component station is about $10,000.

It should be emphasized that in many countries seismologists find great difficulty in developing a science which the governmental authorities regard as a minor speciality of no practical value.

The main difficulties always relate to funds and the recruitment of staff. The second point is particularly disquieting: low salaries and limited chances of promotion too often keep students away from a career in science when there are much more favourable opportunities in industry or private research. Seismological observatories always have too few posts, often not even enough for rotation of the staff doing routine work. Seismological research workers, who are too often isolated, not numerous enough to undertake team work, and sometimes even without sufficient means to maintain adequate libraries are finding it increasingly difficult to keep up with the progress of a science which is continually developing in a few large countries.

An improvement in the present situation can only be achieved through better understanding on the part of national governmental and university authorities and through international aid.

8.3.2 Instrumental study of aftershocks

Field studies of the aftershocks of a major earthquake should make it possible to determine their exact position, in particular their focal depth, and in some cases to follow the migration of the foci along the irregularity which was the site of the main earthquake; they should also make it possible to plot the curve of energy release against time.

In order to carry out this task, national seismological services should be equipped with a number of portable seismographs which can be easily installed in the epicentral area of an earthquake. It should be possible to install them within a few hours after the main shock, so that special means of transport will be required (specially equipped lorries).

8.3.3 <u>Map of seismic zones</u>

A map of seismic zones should be made in each country from the date indicated above: historical research, catalogue of epicentres, map of maximum observed intensities, seismotectonic map, and map of probable maximum intensities.

This map should serve as a basis for applying earthquake protection rules.

It is recommended that meetings of specialists from several neighbouring countries be held, with a view to preparing uniform documents. International collaboration of this kind has been carried out for the Balkan countries (Albania, Bulgaria, Greece, Romania, Turkey, Yugoslavia) and undertaken for the three Maghreb countries (Algeria, Morocco, Tunisia).

The map of seismic zones should also be used in preparing land development projects and, in particular, in drawing up plans for the expansion of towns or villages situated in seismic regions, or for establishing new towns in such regions.

In the latter cases, the map should be supplemented by a "microzoning" map taking account of the geological nature of the different ground surfaces.

The risk of an earthquake should not be the only risk taken into consideration; it should be associated with other natural hazards (floods and landslides, for example) in order to determine the "<u>vulnerability</u>" of areas which may become inhabited.

8.3.4 Earthquake-protection building code

Strict application of an earthquake-protection building code is the most efficient way to reduce future loss of life and material damage due to earthquakes.

Only about thirty countries have so far issued regulations for earthquake-resistant construction or building codes. It is urgent that all countries threatened by earthquakes which have not yet drawn up building regulations for earthquake protection do so as soon as possible.

When they do exist, these regulations are sometimes ignored by engineers and builders; a publicity campaign should therefore be undertaken showing, in particular, how such regulations can be made known to the public.

A special effort should be made to develop simple methods of reinforcing existing dwellings. It is incumbent on the governments of the countries concerned to give the force of law to the texts adopted and to provide for the necessary inspection and penalties for non-observance of the regulations.

8.3.5 Network of accelerometers

In the developing countries there are still far too few accelerometers in use for the measurements already made to be used efficiently. It is therefore recommended that as many instruments as possible be installed in particularly dangerous areas. The recordings obtained should be placed at the disposal of interested research workers.