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Earthquakes, Animals and Man

1. The Earth and Earthquake Prediction

CHAPTER 1 — THE EARTH

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Introduction

Of all natural hazards such as volcanic eruptions, tsunamics, cyclones, droughts, floods and earthquakes, the last are recognised as perhaps the most devastating. They strike without advance notice as to their location, time or severity, and hence throughout history human beings have had to face them helplessly as acts of God. Nothing could curb their destructive force.

Today we have come a long way in our understanding of the nature of earthquakes, which we no longer consider as being entirely acts of God. Earth sciences have established a logical account of their occurrence in place, time and severity. We now know most of earthquake-prone areas of the world, how earthquakes are caused, and some of the signs by which they declare their onslaught in advance. We believe that with a little more understanding we may one day be able to predict earthquakes with reasonable certainty.

The Science of prediction, though young and beset with various unknowns, is advancing fast. We have come a long way and are now able to detect where earthquakes are building up. But we still do not know exactly when they will strike and until we are able to do that, we cannot hope to save human life and property from this hazard.

Our emphasis so far has been on geophysical methods. Several precursory effects such as foreshocks, dilatance, tilting, strain accumulations, emanation of gases, rise or fall of water-tables in wells, can be measured with our modern instrumentation, which has improved beyond imagination during the last 25 years. And yet we are unable to predict with certainty the catastrophic event itself. While strenuous efforts are being directed to the science of prediction all over the world, successful prediction is still a distant hope. We cannot determine the culmination of the process of the building up of an earthquake. The limitations of physical parameters are recognised. We are up against factors which cannot be measured.

The nature and properties of the rocks of the earth's crust, which are involved in the earthquake process, are unknown and will probably remain so for years to come. The same may be said of the nature and intensity of the energy which, by disrupting the parts of the crust gives rise to an earthquake. Predicting earthquakes is therefore not an easy task, although several scientists have bravely attempted it. The danger is always that the physical phenomena may not oblige the scientist precisely as he predicts them. And the panic that may issue between the time of prediction and the time of the predicted event may be more catastrophic than the catastrophe itself. Some scientists, after announcing their prediction, developed cold feet and recanted. Some scientists do anticipate when the event may take place, but fight shy of making any announcement. In brief then, precision and reliability in prediction are still not a scientific possibility. All that can be known with certainty is that an earthquake is building up at a particular place (e.g. in the San Francisco Valley) but exactly when the catastrophe will occur is not predictable yet.

Chinese folklore is replete with instances of how animals, with their sixth sense, can indicate by their abnormal behaviour an impending earthquake. The Chinese have not left the subject to Folk-lore alone. They have studied the subject in their modern laboratories and have involved large numbers of their population in observing animal behaviour before, during and after an earthquake. Conclusions drawn from this behaviour have strengthened

the belief that animals react surprisingly to certain micro-stimuli and by their behaviour foretell the impending catastrophe.

Earthquakes are associated with several physical and chemical changes called precursors. Some of these are perceived by animals through their extra-sensitive faculties. They become frightened and show a reaction of fear and stress.

This is a subject which has been neglected by seismologists perhaps because it smacks of some occult power. Many animals, known to possess acute sense perception before earthquakes, have been subjected to close study in the physical, physiological and psychological laboratories. Studies at the Texas University, by Ruth Buskirk and her colleagues, have confirmed that various animals have faculties beyond the limits of human sensory perception, or even beyond the sensitivity of some modern instrumentation.

Thus, while animal responses to mechanical, electrical, magnetic, ionisation and aerosole impact, and their olfactory responses, have been studied in laboratories in some detail, the geophysicists seem to take no interest in any of these responses. The animal behaviourists of course feel no concern about earthquakes. Admittedly the geophysicists are getting colser to prediction and yet are far away from it. It looks as if we cannot predict earthquakes with the certainty and accuracy that we find in other physical and biological sciences, engineering and to some extent in medicine.

Obviously there is need to combine the two areas of study, physical precursors and animal behaviour. The following pages are primarily a review of the literature already available in the scientific world. If the geophysicists and the students of animal behaviour can join forces we are sure to advance nearer the possibility of predicting earthquakes with more certainty. As Dr Buskirk has aptly summarised the issue, 'although there are gaps in both biological and geophysical information relating to this problem, the gaps in geophysical knowledge are probably larger'. Even if just one earthquake is predicted by animal behaviour, either alone or in combination with geophysical discoveries as is claimed for Haicheng (1975) in China, the world will be better able to meet the scourge of earthquakes and act in a prudent manner to save human life and property.

Equally important is the aspect of preparedness to meet the eventuality. Preparation to meet the earthquake hazard is not an easy task. It concerns the whole of society. It should involve governments, social institutions, educational institutions and ultimately every citizen. After one earthquake, which devastated a whole school, the news media interviewed some child survivors, all of whom positively declared that if they had been taught what to do in such cases at least a few lives could have been saved. Today it has become the normal practice in some foreign countries to teach children to react rationally and without panic in such disaster conditions, and thereby minimise the loss of life.

The Chinese have led the way when they say, 'The People's war against earthquakes must be won'.

Earthquakes

Human society has never been free from struggle against natural calamities which have caused tremendous losses in life and property. Powerless to explain how these disasters were caused men deemed them acts of God. As Science developed, man began to look closely into these natural hazards—volcanoes, tsunamics, typhoons, droughts and famines, floods, lightning strokes, upheavel or subsidence of large areas of ground, earthquakes. Of all these, earthquakes are unique in that they give little or no warning, last for only a few seconds or minutes, but cause untold damage to life and property. They were and still are the most dreaded natural calamity of all. It is no wonder then that early man created a separate god for earthquakes, to be appeased by prayer or sacrifices. In some countries this superstitious attitude still prevails.

As science advanced further man learnt more and more about the earth's surface, its interior, the internal and external processes, and about the changing climate in the atmosphere surrounding him. With the advent of atmospheric geophysics, changes of climate could be predicted to some extent. The movements of the planets around us were studied with increasing accuracy. Transits of planets and eclipses were correctly predicted. Man had a greater liaison with atmospheric conditions and the world of astronomy, largely because they are visible and tangible. But earthquakes remained, and to a large extent still remain, an enigma. We still do not know precisely where, when and with what fury they will strike. All that we know is that they will strike unexpectedly.

An earthquake is defined as an oscillatory movement of the earth's surface, or its crust, as a result of the release of energy within or immediately below the crust. This can happen as a sudden event dislocating segments of the crust. In many areas it is accompanied by volcanic eruption, while in others it strikes all by itself. Deep-seated forces, whose exact nature or strength is not yet fully known, disturb the crust and tend to bulge it up-

wards. When this force exceeds the resistance of the rocks near the surface, the rocks are disrupted and energy is released. An imbalance is thereby established in the sub-surface, which sometimes lasts only for a short while. We call this disruption 'earthquake'.

In the process of rupturing the crust, surface vibrations are set up, caused by seismic waves emanating from the seat of disturbance, which is called the focus. The focus may be as deep as more than a few hundred kilometres below the surface or it may be as near the surface as 10 or 20 km. The velocity of these waves, and the distances to which they will travel, depend upon the source of dislocation, the energy released, and the capacity of the rocks to transmit the waves. Hard rocks will permit the waves to travel faster, whereas softer rocks may absorb the energy partly or even fully. Most earthquakes are felt even at distant places on the earth.

The rupture of the surface may be either a wide gap or a displacement of the adjacent parts called faults. The movement can be lateral, vertical or oblique. If a part of the earth's crust at the surface is already traversed by faults, the damage will occur along the fault planes. The energy transmitted from below will usually tend to follow these faults and ruptures.

The depth of the focus from the surface is known as the focal depth. The point on the surface vertically above the focus is called the epicentre. The damage is maximum in the vicinity of the epicentre and is reduced progressively with distance away from it. The lines drawn on a map of equal damage are known as isoseismal lines, (figure 1).

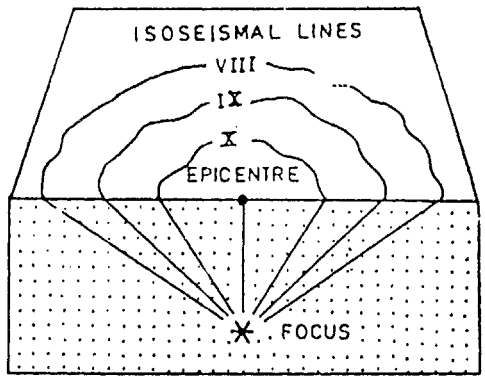


Figure 1 Focus, epicenter and isoseismal lines

Global research is in progress at various centres sustaining laboratories and universities, and an excellent network of communication has been formed through sharing of information and comparing of observation. Earthquakes transcend national boundaries nd, like weather, truly unite the world.

Records of earthquakes grow more scanty and undependable as we go back into the past. It is only since about the 10th century that we have some records of where earthquakes struck, how much damage they did and how many people they killed. As we come closer to the present, records of damage grow fuller and more reliable. The following table shows some recorded earthquakes since about the 13th century. Only those are given in which over 50,000 people perished.

Table 1 *Earthquakes involving 50,000 deaths or above*

Year	Locality	Deaths
1201	Aegean Sea, Greece	— 100,000
1268	Seyhan, Turkey	— 60,000
1268	Cilicia, Asia Minor	— 60,000
1290	Jehol, China	— 100,000
1456	Naples, Italy	— 60,000
1556	Shensi, China	— 830,000
1667	Shemaka, Iran	— 80,000
1693	Naples, Italy	— 93,000
1695	Linfen Zianghi, China	— 100,000
1731	Peking, China	— 100,000
1737	Calcutta, India	— 300,000
1739	Yunchaen, China	— 50,000
1755	Lisbon, Portugal	— 60,000
1783	Calabria, Italy	— 50,000
1908	Messina, Italy	— 83,000
1920	Kansu, China	— 180,000
1923	Tokyo, Japan	— 143,000
1927	Nanshan, China	— 200,000
1932	Kansu, China	— 70,000
1935	Quetta, Pakistan	— 60,000
1960	Agadar, Morocco	— 66,000
1976	Tangshan, China	— 655,000

These figures appear large compared with deaths occurring in the more numerous but smaller earthquakes. The total deaths caused by earthquakes so far run into many millions, with an estimate of about 100,000 deaths occurring every year. The actual recorded deaths so far amount to 5,000,000. China heads the list with about 2,000,000 deaths; Japan has more than 500,000, Italy more than

370,000 and India more than 350,000. The year 1976 can be called the catastrophic year in which nearly 700,000 people died. The highest toll of lives in one single earthquake, at Shensi, China in 1556, is reported to have been at least 830,000.

The number of casualties will obviously depend upon the time of day at which the earthquake strikes. If it is at night, when most people are indoors, the casualties are more. The earthquake seldom kills directly; it kills through the collapse of houses, bridges and other installations, through falling trees, and sometimes by consequent fires, floods and ensuing epidemics. Records of such collapses and their consequences are by no means complete. Damage caused to property is almost incalculable because correct estimates are seldom made. According to Berlin the total damage in U.S. alone up to 1975 was estimated at some 2000 million U.S. dollars. Globally it will be several times this amount. With modern technology in the construction of earthquake-proof structures, the losses from falling buildings and consequent deaths, will, it is hoped, be progressively reduced.

Due to a population growth over the globe of several millions per year, the risk to life is ever increasing. If, say in 1800, 100 people died at a particular place in an earthquake, today an earthquake of the same intensity, striking the same spot might cause the deaths of several times that number. Developments in urbanisation, industrialisation and communication are increasing at an accelerated rate. Urbanisation gives rise to concentrations of people and consequently the risk of life also increases. One earthquake in a 'developed' area will kill more people, and destroy more wealth, than perhaps a hundred earthquakes of the same magnitude in 'undeveloped' areas or in the wilderness.

The risk to human society is therefore growing at an alarming rate, and the need to study the causes of earthquakes for the purpose of prediction grows correspondingly more acute. A systematic study of earthquake science leading to reliable prediction is therefore of the highest urgency; to pursue this study by all appropriate methods, conventional or other, is the need of the hour.

Interior of the Earth

The crust of the earth is recognised as a comparatively thin layer of rocks whose upper surface is perpetually exposed to the atmosphere and the waters of the seas and oceans. The rocks exposed on the surface exhibit a wide variety of physical characters. As the surface rocks were studied it became apparent that the crust is not uniform all over the globe either laterally or vertically. Rocks differ in their chemical composition and physical properties such as density, hardness, resistance to shock waves, etc. On the surface they are exposed to the vagaries of climate, the sun, rain, snow and wind, and the weather into softer and finer materials like sand and clay which are carried by streams and rivers to the seas and oceans.

The total thickness of the earth's crust accessible to man so far by direct excavations in mines, is not more than some five kilometres. The deepest borehole made by man so far extends to 12 km from the surface. As the depth increases the type of rocks and their physical properties become more and more indistinct and uncertain.

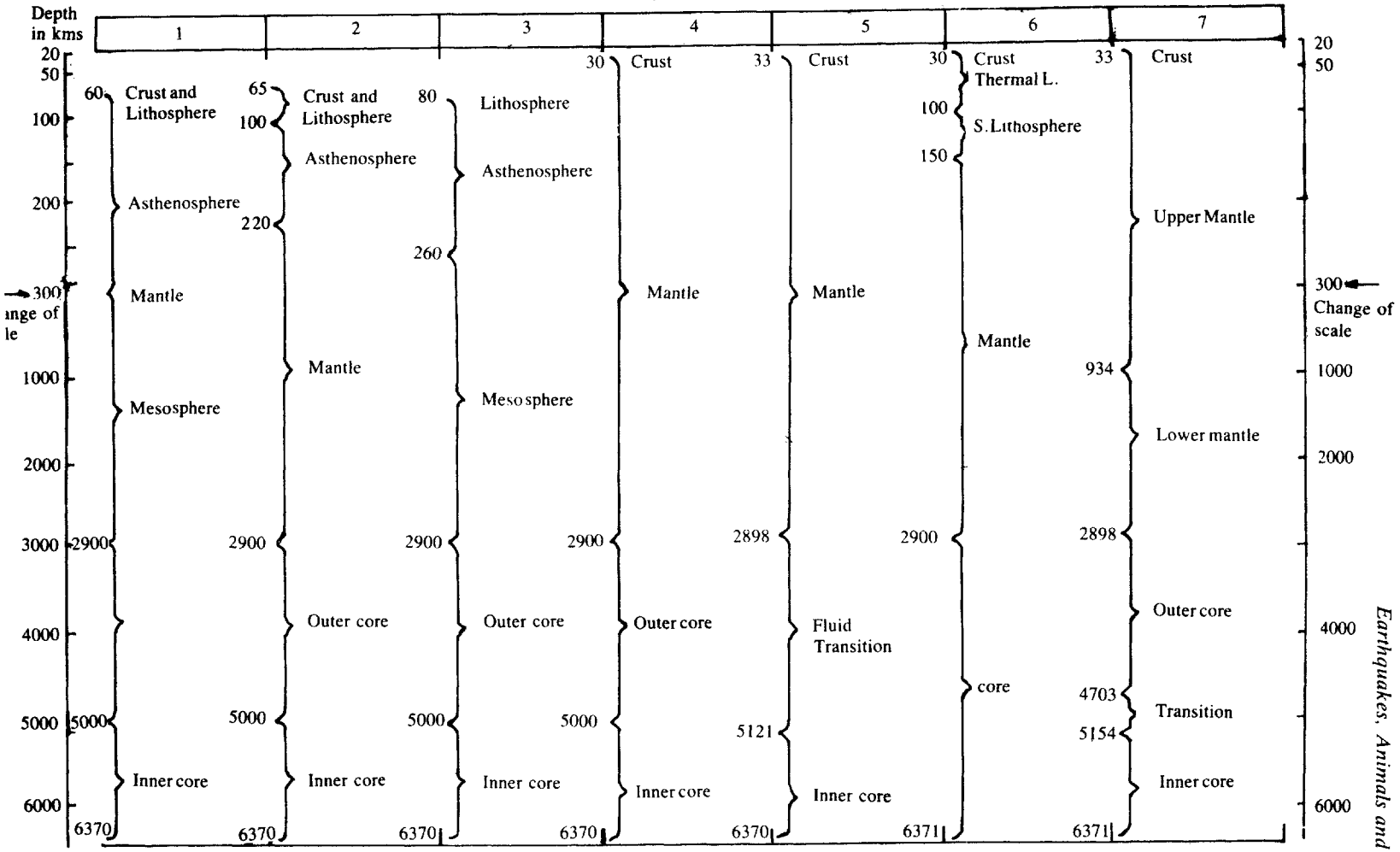
The crust is found to extend down to a depth of some 20 km below the seas and oceans and about 70 km below the continents and mountains. It consists of a variety of rocks classified into the sial, a lighter set of rocks comprising silica and alumina, and the sima, a heavier set of rocks comprising silica and magnesia.

The maximum information we have so far of the interior of the earth is through the earth's own seismicity as observed in earthquakes. Artificial seismicity, i.e. the shock waves created by man-made explosions on or near the surface, gives us some information to a depth of some 30–40 km through Deep Seismic Soundings (DSS) (Kaila et al. 1976). But here also it is uncertain whether the deeper signals are originals or the multiples caused by refraction of waves from the same rocks giving an exaggerated sense of depth. Besides the seismic method, the gravity and magnetic methods, and to some extent Deep Electrical Soundings (DES) have also thrown some light on the top few kilometres of the earth's surface.

However, it is natural seismicity which has been chiefly responsible for our knowledge of the interior of the earth. The results lack precision because the interpretation of the seismic signals depends upon our basic concept or estimation of the rocks below, especially under their conditions of high temperature and pressure, both of which increase steeply, far beyond our experience on the surface. A few models of the interior of the earth, as seen or imagined by physical geologists, are given in table 2.

As will be apparent, these models vary widely and there is no unanimity amongst these authorities regarding the exact nature of the interior, the different segments, their thicknesses and their character. Within about 400 km from the surface several layers are postulated such as lithosphere, asthenosphere, mesosphere, mantle, etc. but the precise distinction between them is not very clear. There is a general agreement that the outer core begins at a

Table 2 *Interior of the earth–different models*



1. C. Ollier, Tectonics and Landforms (1981); *2:* Peter Link, Basic Petroleum Geology (1982); 3: Cambridge Encyclopedia- of Earth Science (1982); 4 Richter, *Elementary Seismology* (1969); 5: *Jacob, Russell and Wilson, Physics and Geology* (1983); 6. University of texas, 7: Arthur Holmes, *Principles of Physical geology (1966).*

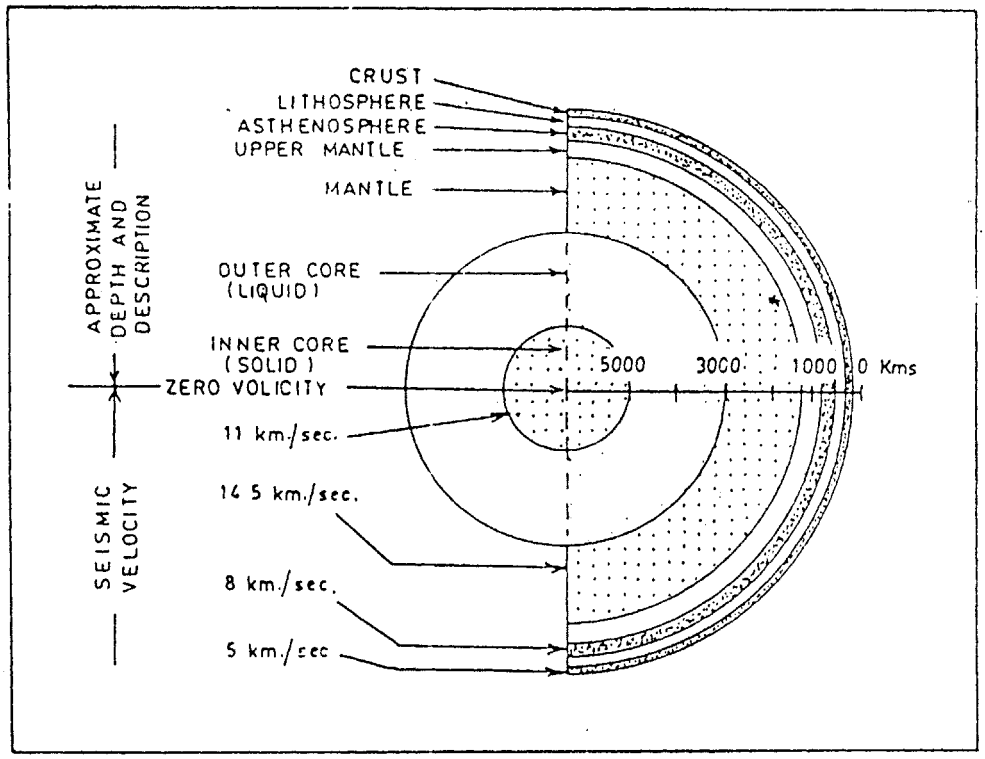


Figure 2 Interior of the earth (see version table 2)

depth of about 2900 km indicated by the Gutenberg discontinuity, the inner core at about 5000 km, and that the total depth to the centre is 6371 km from the surface (figure 2).

One of the most recent studies on the interior of the earth was made during a workshop by the University of Texas at Austin, in March 1982. According to John Maxwell, writing in April 1984, the wide variety in the different prevailing models was examined and an attempt was made to reconcile the discrepancies.

The workshop addressed itself in particular to separating the crust from the upper mantle. The two seismic discontinuities, the Mohorovicic discontinuity (or Moho) that separates the crust and the mantle, and the Gutenberg discontinuity which separates the mantle from the core, have been known for years although their precise character is still uncertain. The Moho is recognised as the seismic discontinuity below the crust but its nature is still conjectural. The Gutenberg discontinuity is recognised between the mantle and the core as a zone of scatter in seismic velocities. Similarly, seismic discontinuities have been recognised as depths of 650, 400 and 220 kms from the surface. The study goes on to say that the 650 km discontinuity is close to the maximum depth of observed earthquakes. In brief, this workshop endorsed a fresh model of crust down to 30 km, lithosphere down to 150 km, mantle, upper and lower, down to 2900 km, outer core down to 5000 km and the core down to the centre at 6371 km.

For the purpose of the generation of earthquakes we are concerned with the part within the mantle down to about 700 km from the surface. The foci of most earthquakes are located within the upper mantle and the crust.

It is noteworthy that we are uncertain about the exact physical nature of these imaginary layers of the earth. Their density, homogeneity, elastic limit, water content, faults etc. are important for

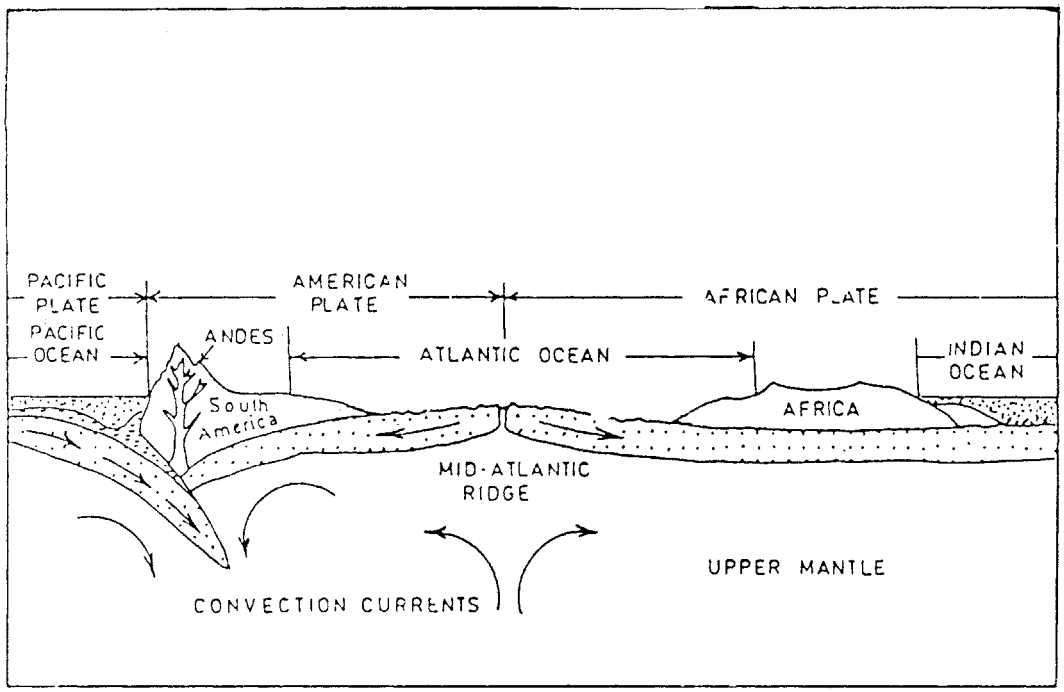


Figure 3 Interior of the earth; movements of plates and convection currents (after Geodynamics)

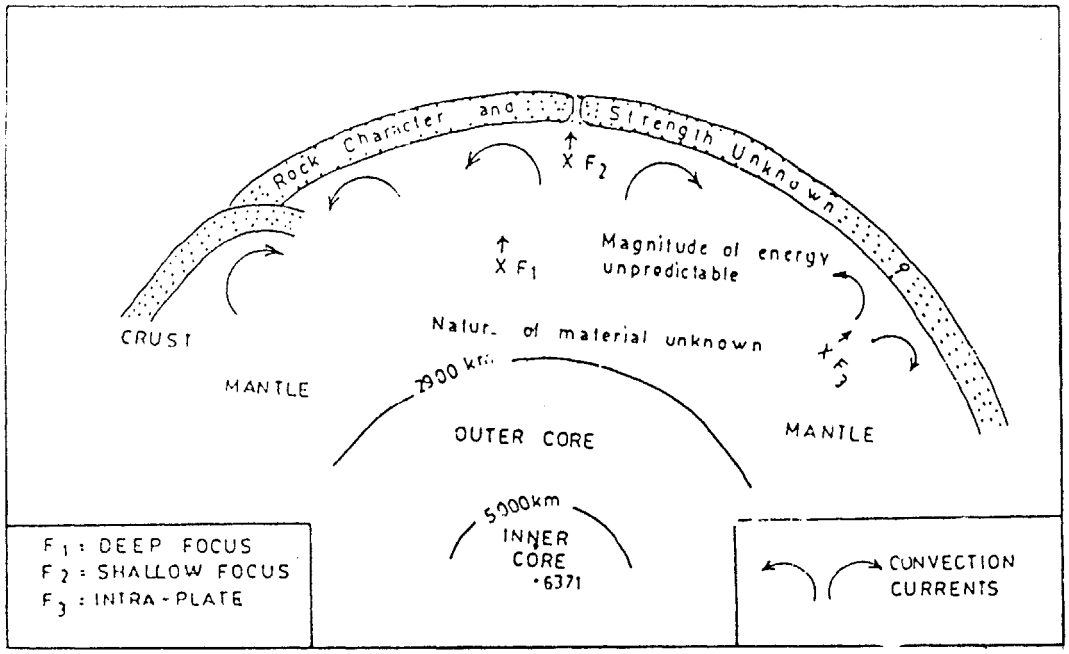


Figure 4 Interior of the earth with unknowns

the consideration of the source of earthquakes, the propagation of earthquake waves, and the point at which the rocks at the surface will 'rupture' and give rise to earthquakes. Our ability to predict earthquakes precisely, with regard to the exact geographical location, time, intensity of the shock and degree of probability or reliability, is seriously limited by this lack of knowledge of the exact condition of the rocks forming the interior of the earth.

The workshop further deliberated on some aspects of plate tectonics. It noted a wide agreement, it states, 'that the basic Driving Mechanism is some form of convection currents in which the lithosphere itself may be an active component'. We know very little about the exact nature and force exerted by these convection currents in pushing and pulling the plates (figures 3 and 4).

Continental Drift

A close look at the map of world suggests that the present configurations of the continents are not altogether unrelated to each other. If you were to cut a cardboard sheet into the shapes of the present continents all on the same scale, you could fit North America, South America, Africa and Antarctica into a more or less compact block. India and Australia would also fit neatly into this block. The fit is so convincing that one begins to wonder whether in the geological past such a situation (figure 6) could have prevailed.

Such a convincing fit of the land masses cannot be a mere accident. There must be deep-seated reasons for the way in which the once interlocked continents separated from each other. Many internal processes were suspected but there was no evidence that continents could move away from each other in this manner.

Wegenor (1912) for the first time expounded his favourite hypothesis of Continental Drift in which the Americas were separated from Africa, India, Antarctica and Australia. He supported his argument by collecting information on the plant and animal life, both fossils and living species, on the facing sides of the parted continents, and his study showed a remarkable resemblance of plant life on both the facing sides.

Wegener examined this in a variety of ways. He hit upon the concept of palaeomagnetism, that is, the earth's magnetism in past geological periods. There was distinct evidence that the polarity of the earth was subjected to sudden changes. This was most evident at places midway between the drifting continents. In order to understand the gaps created by shifting continents, the seas in between the continents were searched for evidence. Some prominent ridges were noticed in mid-ocean and were named Mid-Oceanic Ridges. These ridges were flanked by rocks which showed bands of reversed magnetic polarity, similar on either side of the ridge centres.

The discovery of Mid-Oceanic Ridges, and the pattern of palaeomagnetism substantiated the theory of drifting continents. It is known that hot rock does not acquire any magnetism but as it cools it acquires the magnetism imprint of the time. Thus the Mid-Oceanic Ridges, on closer study, are found to comprise strips of reversed polarity, almost mirror images seen from the centre of a ridge. It was argued that as continents moved away, new magma welled up along the central line of the ridge. There are many other evidences, such as the transverse faults, which cannot fail to impress an observer of the sea-floor maps of today.

According to Ollier (1981) the present 'normal' magnetic direction was implanted not more than about 700,000 years ago. Before that, the polarity was reversed from as far back as some 2,400,000 years ago. These changes of polarity are known as Brunhas (normal) and Matuyanas (reversed) epochs. There were frequent magnetic reversals. All these observations provided an explanation for the gaps in the drifting continents.

Piecing together such evidence, it was postulated that the continents were joined together upto a certain point of time in the geological history of the earth. By the Permian period, that is some 200 million years ago, they started separating from each other. The Southern Continent of Gondwana broke up, the split started beginning with separation of South America from Africa, and of India from Antarctica and Australia. These two separated land masses further separated into different blocks that moved in different directions at different speeds to reach their present positions.

Wegener found that till about the Permian time the flora and fauna were contiguous and showed similarity in their forms and growth. The rocks on the adjacent continents were found to be not merely similar but identical, leaving no doubt that they had formed one single unit before the split. Even the mineral deposits were similar. The huge ice-sheet, which formerly spread over the once contiguous area, left identical 'foot-prints' on either continent.

The Gondwana continent which comprised Africa, India, Australia and Antarctica had a surprisingly similar evolution of plant and animal life up to the Mesozoic era. The Mesozoic, characterised as the Age of Reptiles, saw a growth of reptiles on all sides. Similarly, the large-scale occurrence of coal testified to the profuse growth of large leafy

plants like Glossopteris and Gangamopteris. Large deposits of coal, and numerous fossils of similar types of land animals and plants, were found in South America, South Africa, Australia and India.

Thus there were several collateral evidences to support the Continental Drift Theory, even though there were many loose ends still to be tied up. If continents were to move, they must be riding or floating on some plastic rocks below. What were these rocks like? Besides, if such huge land masses were to be moved a few centimetres every year, or snap suddenly at the crust on the boundaries of continents, as in an earthquake or a valcano, what is the provocation or the source of such tremendous energy for the movement of millions of cubic kilometres? The answers to these questions were eagerly awaited

Plate Tectonics

All the separated land masses, and the oceanic ridges in between them, led to the supposition that the crust must be divided into segments or plates which are in continuous motion. This means that these plates move towards each other in some areas and away from each other in other areas. When they move towards each other, one of the two plates submerges or dips, allowing the other to ride over it (figure 5). The subduction zone is marked on the surface by island arcs and volcanoes, with attendant phenomena of earthquake.

The other edges move away from each other, and the gaps are marked by a steady effusion of lava which cools in contact with water and builds up a Mid-Ocean Ridge. The up-welling lava thus pushes the plates further and further away from each other. These are the Mid-Oceanic Ridges which are outstanding features of the Pacific and the Atlantic oceans. The sites of these on the sea-floor map of the world offer impressive evidence about the mechanics of plate tectonics.

The expression 'plate tectonics' summarises the dynamic processes operating between the upper mantle, the asthenosphere and the lithosphere. The continents and the tectonic plates can move in three different ways. They can be described as having divergent, convergent or transverse motion. In consequence there are separations, collisions and oblique movements of the plates and hence of the continents.

If the continents drifted away from the median line of the Mid-Oceanic Ridges, what was happening at the other end of the continents? If the continents were to move continuously in one direction what would happen between two continents moving away from each other. Cary (1926) would have us believe that this is in fact happening as propounded in his thesis of an Expanding Earth. However, the vital statistics of the earth do not seem to justify such a hypothesis, and the enigma of continuous unidirectional movements, without submergence to compensate, remains unsolved.

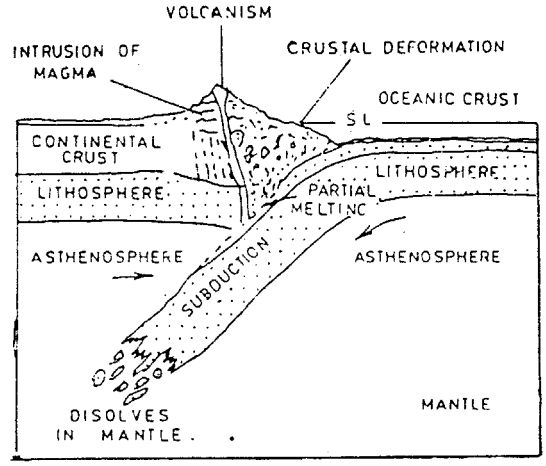


Figure 5 Converging plates, subduction zone (After Peter Link)

Simultaneously, Arthur Holmes and D T Griggs (1966) propounded that the crust resting on the mantle was constantly being pushed around by the internal convection currents. These currents then provided the motive force and the energy for the land masses and continents to migrate or move so long as other crustal conditions were favourable. Convection currents in the mantle thus provided one missing link for the movement of continents. These convection currents are deep-seated, well below the crustal cover, in the upper mantle. The movement imparted by them could not be more than a few centimetres per year because of the millions of cubic km of the crustal parts involved. The rate of this movement is some 5 to 6 cm/year. That is the rate at which continents have been moving apart from each other in the continental drift. Working backwards, one can estimate when the movement could have started in each case.

The Mid-Oceanic Ridges are formed where the convection currents push the fluid upwards towards the surface, where the lava is able to penetrate the crust. When the lava is unable to penetrate, earthquakes are caused. Volcanoes are often accompanied by eartyhquakes, but earthquakes can occur without any volcanic eruption.

Thus earthquakes can be attributed to a differential motion between adjacent plates whether they are converging, diverging or moving transversely. At the Oceanic Ridges the adjacent plates are separating on account of the tension caused by the provocative movement and up-welling of the magma in the Upper Mantle. When plates converge the constant friction causes movement of large masses of plates giving rise to earthquakes, sometimes accompanied by volcanoes. The location of different plates, active spreading ridges and the likely direction of their motion is indicated in figure 6.

There are several versions recognised for the names and number of the plates. However, all earth scientists agree that there are at least 15 different recognisable plates as given by the *Cambridge Encyclopedia of Earth Sciences (1981):*

A, North America
B, Caribbean
C, South America
D, Scotia
E, Eurasian
F, Hellenic
G, African
H, Arabian
I, Iranian
J, Indo-Australian
K, Philippine
L, Pacific
M, Cocos
N, Nazca
O, Antarctic

The dynamics of Plate Tectonics demands the presence of areas where the plates are diverging. The following active spreading ridges are recognised by the same source:

1. Reykjanes
2. Mid-Atlantic
3. Carlsberg
4. South-West Indian
5. Mid-Indian
6. South-east Indian
7. Antarctic-Pacific
8. East Pacific rise
9. Cocos
10. Nazca

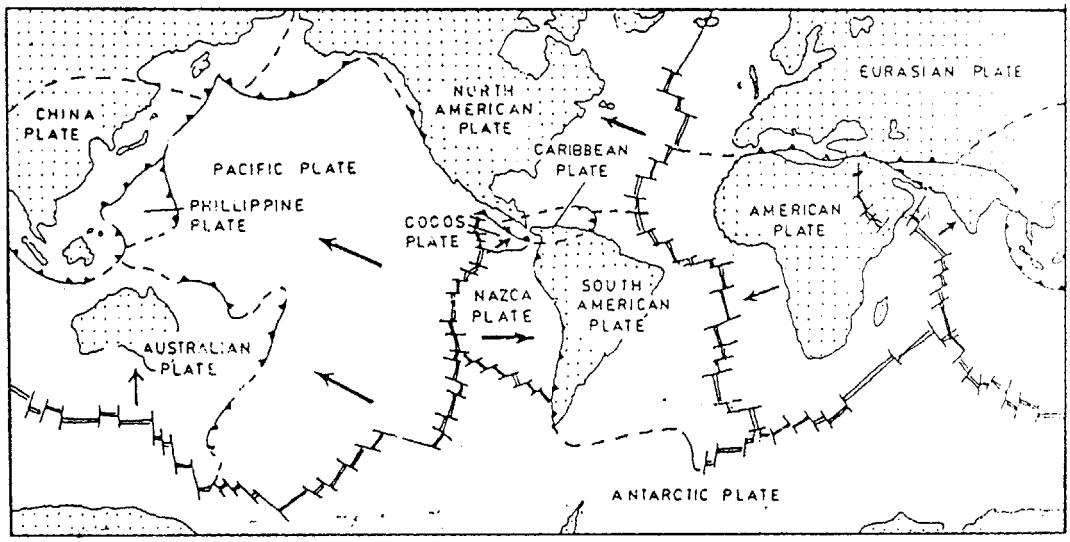


Figure 6 Major Tectonic Plates

The Unstable Earth

The earth has been undergoing constant changes, both on the surface and within. The expression 'terra firma', implying that the earth is stable, is perhaps correct only so far as it relates to the period of human history, which is but a small speck in the 4.6 billion years of the earth's existence. Besides the movements on the surface, like drifting continents and mountain building, there are other movements within the asthenosphere and the upper mantle which likewise give rise to volcanic eruptions and earthquakes.

Rocks when subjected to stresses from below or from the sides yield in a variety of ways such as brittle deformation, that is, yielding by breaking into blocks. The deep-seated rocks, due to high temperature and pressure, yield by plastic deformation which can reverse if the stresses are released. Thus the pile of rocks, from the surface to depths of several tens of kilometres, behaves differently in different parts of the globe according to their strength, the presence or absence of water, presence of faults and shears, the magnitude of the deforming forces, and the temperature and pressure at which they are subjected to these stresses.

Mountain-Building Process

There are continuous changes in the physiognomy of the earth's surface. The rocks on the surface are subjected to rain, sun, wind, frost and other forces. In consequence they crumble into pieces and eventually turn into fine sand and clay. These sediments are carried away by rivers and deposited in the seas as a continuous process throughout several geological epochs. This process may be seen even today after a shower of rain. Through this, the mountains are eroded and the sea floors become heavier. By simple logic, this is apt to cause tension between the mountains as they get progressively lighter and the adjacent sea-beds as they get heavier. A disruption is inevitable. At the junction, the crust breaks up and adjusts itself to attain a new equilibrium. This adjustment is accompanied by movements of large masses which can cause earthquakes.

This process is easier to grasp if we presume that the crust is resting, or rather floating, on a molten mass of magma in the upper mantle. Rocks of both land and seas are balanced over this fluid in an isostatic equilibrium. Isostacy is the process of adjustment between masses so that there is equilibrium at the junction of the Upper Mantle and the lithosphere. Pratt postulates that the different parts of the lithosphere have different densities but float on a uniformly dense medium or substratum. The lighter masses of rocks float higher, forming mountains, while the denser rocks form basins and lowlands. This is indicated by a heavier basalt layer below the seas compensated by high mountains and the deeper roots of lighter rocks. In other words, the density differential is compensated by the larger thickness of the lighter rocks below mountains and the comparatively thinner crust below seas. consequently any disturbance in this balance is apt to result in readjustments expressed as faults or ruptures. These are often accompanied by movements within the crust which cause local or even regional earthquakes.

Again, large sedimentary basins, which continue to receive sediments for long geological periods, are also subjected not only to a vertical rising or sinking process but are disturbed laterally by earth movements. In consequence the deep basins or geosynclines are subjected to severe vertical and lateral compressive forces. The rocks are folded, and when the stress exceeds the limits of their strength, are faulted. There is thus a continuous movement in the earth's crust, which has given rise to the expression of "the unstable earth".

Such epochs of folding and occasional faulting continued for long periods of time in geological history. Various series of mountain ranges were generated in this manner. The final size and shape of the resultant uplift or displacements will depend upon the numerous forces acting upon the region and the competance of the rocks involved. Such well-known mountain ranges as the Rockies, the Andes, and the Alpine-Himalayan Range are classic examples of orogenic mountains. These processes are in continuous operation and their movements frequently generate earthquakes and volcanoes. Mountain ranges are therefore also seats of earthquakes. These areas are already known and we can anticipate and keep watch wherever such potentially vulnerable areas exist.

The past records of earthquakes and their epicentres shown unmistakably that the epicentres of a large percentage of earthquakes are clustered round these orogenic belts. It is therefore reasonable to anticipate that future earthquakes will also be generated around these areas. Several areas in the world, like Sun Francisco region, are heavily instrumented to give indications of on-coming earthquakes.

Seismic Waves and Their Propagation

Any agitation or movement originating within the crust or the mantle is communicated to the rocks above. These shock waves on reaching the surface become earthquake waves. Several kinds of seismic waves are recognised. The P (or Primary) waves emanate from the focus and travelling vertically reach the surface at the epicentre. Some waves travel through the interior of the earth radially outwards and reach the surface of the earth. P-waves travel in a vertical plane as compression and rarefaction waves. These are the fas-

test waves and reach different parts of the globe earlier than any other waves. The velocity with which they travel will depend upon the density and other physical characters of the rocks. The second set of waves called S (or Secondary) waves vibrate from side to side in a horizontal plane and arrive later. The Love waves, or the surface waves, travel in a circular propagation like ripples in a lake caused by dropping a stone. These are the last ones to arrive.

The waves caused by the disturbance at the focus are propagated in three dimensions. Some travel continuously in the same direction, others get reflected and refracted by the rocks they pass through. Within 100 km of the surface there are two layers of rocks in so far as the velocities of the waves are concerned. In the upper layer the waves travel slower while in the lower one they travel faster. The junction between the two layers is the Mohorovicic discontinuity.

This change in the velocities at the Moho is attributed to a sudden change in the physical properties, without any chemical change, of the mantle. The mesosphere which lies below the mantle is a low-velocity layer. This suggests that the interior of the earth is not uniform for the propagation of seismic waves. Hence, depending upon where the focus of disturbance lies, the propagation of waves vertically to the surface and radially away from the epicentre is a complicated phenomenon not amenable to easy interpretation or anticipation. Once the waves reach the surface, we can more accurately measure them through elaborate instrumentation. As the culminating point of the phenomena of earthquakes is reached in a matter of seconds, there is little or no time to forestall it and get ready to meet the emergency. It is only from the earlier indications of where the earthquakes are building up that the event can be anticipated, and that too in a general manner.

All this time we have been considering the strength and the conditions of the rock material within which the focus is generated and from which the waves are set in motion. We have not yet thought of the 'source' or provocation for the disturbance. Much will depend upon the intensity and the nature of this source which, moreover, is not amenable to any estimate of its intensity or its precise point of application. Since the earthquake affects a volume of millions of cubic kilometres of rock the provocation for such a colossal movement must be correspondingly big. We are yet very uncertain about the exact nature of this provocation.

Thus we neither know the strength of the rock-mass involved in an earthquake nor the nature of the energy source that causes this disturbance.

Habitat of Earthquakes

We have seen that the plates, or large segments of the earth's crust, are independent of each other and yet in touch with each other, connected in such a manner that displacement can occur only at their junctions. What is not quite certain is the Driving Mechanism which causes them to move. The most widely accepted mechanism is the thermal convection system that operates at the base of the plates in the lithosphere or mantle. Several models have been imagined relating to the plates number, size, shape and depth, and the direction of the movements that push them away from each other or make them clash with each other, as at the subduction zones.

The epicentres of all earthquakes, big and small, when plotted on the world map are found to be mainly along the plate boundaries. Prominent alignments are along the Rockies, Andes, Alps and Himalayas-Arakans. Another prominent chain of epicentres is found in the Pacific Ocean. It is called the Pacific Girdle or, since the earthquakes and volcanoes often occur together, the Pacific Ring of Fire.

The majority of earthquakes are clustered along the regions where the plate boundaries are under constant tension. The plate sutures are therefore marked as the habitat of earthquakes. All along these regions earthquakes are building up. This can be demonstrated by various measurements of displacements of land, tilts, bulges and development of faults and ruptures. Earthquakes are expected along these regions and they are watched.

According to the earliest pattern of seismicity outlined by Richter (1969), the seismic belts were divided into some seven regions of decreasing seismicity such as: (i) Circum-Pacific, (ii) Alpide-Asia, (iii) ocean ridges, (iv) continental rift zones, (v) active areas marginal to the continents, (vi) areas of older orogenies, and (vii) stable continental masses.

The recent concept of Plate Tectonics has added more precise areas of the plate boundaries. The U.S. Department of Commerce's Environmental Science Service Administration (ESSA) has recognised the following regions in 1970, arranged in a sequence of decreasing seismic intensity.

1. All plate boundaries in the Atlantic, Pacific and Indian Oceans
2. Ocean Ridges of the Indian Ocean and the Atlantic Ocean in the Northern Hemisphere
3. Mid-Atlantic Ridge in the Northern Hemisphere
4. Alpide-Asia and Western North America
5. Aleutian and Kurile Islands
6. East African Rift Zone
7. Eastern Mediterranean region
8. Turkey to Hindukush Mountains and Caucasus Mountains to Persian Gulf
9. North China, especially the triple junction involving Eurasian, Indian-Australian and Pacific Plates
10. Alaska
11. Western U.S. from California eastwards
12. Arizona, Eastern Idaho, Western Wyoming and terminating in north-western Montana
13. Precambrian shield areas of India, Canada, Brazil, Australia, Siberia and Africa

The alignments of earthquakes are thus known. The width along which they will occur will depend upon the local geology of rocks and their strength to resist the forces of deformation. When the tension is building up, minor indications are perceived on the surface. As the tension continues, a point is reached at which the rocks cannot contain the deforming forces, and the rocks snap on the surface causing earthquakes. These indications are called precursors (see p. 565 for details).

Thus the plate margins are known areas where earthquakes are expected to occur. As each earthquake involves the snapping of rocks with a release of energy, that area is afterwards quiet for a while, until the tension builds up again. However, between two areas where the internal tension has been released, there are gaps which are still under continuing tension.

On the whole, a larger number of earthquakes are associated with convergent and transform boundaries than with divergent plate boundaries.

The sheild areas are by and large free from tectonic disturbances except when regional faults and rifts are generated as in the Great African Rift. However, the sense of immunity which the shield areas have enjoyed so far is being eroded by a number of Intra-plate earthquakes, which have occurred right in the middle of shield areas, where there had been no signs of tectonic weakness.

Seismic Gaps

The plate boundaries are thus the areas which are especially vulnerable to earthquakes because some tension is growing there all the time. The energy keeps on building up and is released only when or where the rocks are unable to contain the stress any longer, with a resulting earthquake. This happens in small segments of the plate boundary. Where the earthquake has not taken place, the stresses continue to build up. These are the 'seismic gaps', which are prone to future earthquakes.

Dr S A Fedotov was the first to recognise the strange fact that along plate boundaries, the earthquakes do not occur with any continuity but are cut off as if intercepted by a cross fault. Thus between two earthquakes, in an alignment, there are well-defined gaps.

Later, in 1968, Dr Kiyo Mogi pursued Fedotov's idea and used the concept as a precursor, emphasising that these gaps are likely to be the scene of future earthquakes. Dr Alexander George (1979) of Lamont-Doherty Laboratory brought out a remarkable map of the Pacific Girdle. He graded the gaps into six categories in order of decreasing risk. Some of the 1 and 2 category gaps have resulted in earthquake upto magnitude from 4 to 6. "Today", he adds, 'our error margin is 30 to 40 or more years. Soon we may close on 10 to 15 years.'

An idea of the areal extent of these gaps obtained from the Vakatago seismic gap, in the South Central Alaska, which is estimated to be about 250 km long and 150 km wide.

Even though some earthquakes—Hokkaido 1969, Kamachatka 1971, Antilles 1974 and Peru 1974 among others—were predicted within the seismic gaps, in none of these the time element could be predicted with the desired precision.

Summarising the role of the Seismic Gap Theory, Tatsch (1977) considers that it suffers from the following weaknesses:

(a) not all earthquakes occur within seismic gaps,

(b) some seismic gaps existed for centuries without experiencing any earthquake, and

(c) the concept predicts, where some earthquakes may occur but not when they may occur

All these defects could adversely affect the utility of the seismic gap theory for earthquake prediction.

The seismic gaps are regions of high seismic potential that are likely to produce large earthquakes within the next few decades. They are areas along the convergent, divergent or transverse plate boundaries where large earthquakes have occurred in the past but not within the last 25 to 40 years or so. Thus the seismic gaps are temporarily quiet zones where strain is building up and is most likely to result in an earthquake. This theory has contributed substantially to the science of prediction.

Intra-Plate Earthquakes

Apart from the plate boundaries, which form the natural habitat of earthquakes, some interior areas of the continents also appear susceptible to earthquakes. The African Rift Valley is a natural zone of weakness although large earthquakes have not occurred there during human knowledge. From recent records the central parts of continents or subcontinents like North America, South America, Australia and India seem to be equally vulnerable to earthquakes. Plate tectonics does not account for such movements within the continents. The reasons for such earthquakes are not obvious, but their occurrence has awakened us to such possibilities.

One of the most devastating intra-plate earthquakes occurred on 16 December 1981 when New Madrid (West of the Mississipi river, USA) was rudely shaken by a series of earthquake shocks. The New Madrid fault zone was suddenly activated giving rise to the quake. Large fissures were opened up, mud and sand were ejected, and land levels were disturbed. The felt area extended over some 200 km away from the epicentre which was found to be close to New Madrid town. Roughly 6 million sq. km. were affected. This is a much larger area than the one that was affected by the San Francisco earthquake (Inter-plate) of 1906 where the felt area covered some 150,000 sq.km.

Other intra-plate earthquakes are: Charleston, South Carolina, 1886; Grand Banks, Newfoundland, 1929; Koyana, India, 1967; Meckering, Australia, 1968; Cape Ann, Massachussetts, 1977, Eastern North America is one of the most seismically active intra-plate regions. More than 1000 earthquakes have been reported, according to Berlin (1976), east of the Mississippi River since 1700.

Nuttli, a seismologist of St. Louis University, and his colleagues recognised the new likely areas of earthquakes, the Intra-plate ones. What struck them most was that Inter-plate earthquakes can be anticipated whereas the Intra-plate ones are still an enigma. Therefore, the danger to society can be greater from Intra-plate earthquakes because such earthquakes can strike at unexpected places and time and with unexpected magnitudes, causing grave danger to life and property.

While it is not quite clear how the intra-plate earthquakes originate, in the context of the plate-tectonics, Sykes and Sbar, according to Berlin (1976), analysed some 80 of these and found that most of these events were characterised by thrust faulting. All were of shallow focus and occurred in horizontal segments of lithospheric plates. The fundamental mechanism of convection currents is the ultimate source for this colossal energy. These convection currents are also generated below the central parts of plates and activate relative displacements within the plates.

Intra-plate earthquakes are found on nearly every continent. Most of the shield areas of the world are considered as immune to earthquakes, at least major ones. Australia is a well-known shield area of the world. On the basis of Plate Tectonics this continent should be free from earthquakes. However, between 1938 and 1941 four moderately strong earthquakes occurred on the West Australia shield. The earthquake of June 1941 was of the magnitude 6.75 which is not an insignificant magnitude for any area. Again, a damaging shock of 6.8 magnitude occurred at Meckering, Western Australia on 14 October, 1968 (Rikitake 1976). Since there is no tectonic logic in their occurrence, the Intra-plate earthquakes are even more unpredictable than those occurring along the plate boundaries, which are recognised as vulnerable. They sometimes cause greater damage and are truly a bolt from the blue.

Nature of Earthquakes

More earthquakes strike at night than during the day. They cause shaking of the ground and open

gaping fissures; the ground movements cause collapse of houses and other structures and installations. They damage water supply installations including pipe lines, also sewerage and electrical installations. Other effects are landslides, avalanches, ground subsidence, liquefaction, ground fissuring, tsunamis, seiches; often fires are started through electrical misconnections. Earthquakes kill very few people directly; the loss of life is largely due to the roof collapses and people being killed by falling debris or being trapped under the debris.

The damage to property is roughly proportional to the ground movement and to the state of development of the area. In U.S. alone up to 1975 about two billion dollars' worth of damage to property was estimated. Between 1975 and today the damage in U.S. has been almost as much because the urbanisation has been progressing at a prodigious rate, with a correspondingly higher loss of life. According to Berlin (1976) the 1906 San Franscisco quake affected a population of 500,000 with a death toll of about 700. A repetition of this earthquake at the same place today would affect more than 5,000,000 Californians.

A heavy rate of population growth and tremendous increase in urbanisation and installations all over the globe, have greatly aggravated the risk from earthquakes.

Some earthquakes which are small and of purely local significance, cause scare but no damage. Some are so small in magnitude that they can be detected only by instruments. A fairly large number do cause damage but not much loss of life. Only a few cause enormous damage, devastation and death. On an average about 50,000 felt earthquakes, affect the surface of the earth annually, of which over a 100 do serious damage. Great earthquakes killing thousands of people occur about once a year. A list of earthquakes causing over 50,000 deaths is given in table 1.

Since the seas and oceans cover a large area of the globe, many quakes occur on the sea floor and are called marine earthquakes. They cause no visible damage to human society and are not even noticed by human beings. They cause tsunamis, or exceptionally heavy waves, which cause loss of marine life and devastation in coastal areas.

Thus a comparatively smaller number of quakes affect the land. Those whose epicentres are far away from civilization do not cause much damage. The severity of an earthquake is measured according to the area over which it is felt or damage it caused, and the amplitude of the vertical or lateral movements of land. The magnitude of the damage on the surface is also a measure of the energy released by the earthquake at the focus. By far the most effective criteria for evaluating the damage due to an earthquake are the loss of life caused immediately by movement of the ground with resultant collapse of houses and installations, or subsequently by floods, famine, fires and associated diseases.

Causes of Earthquakes

Earthquakes have occurred since the early history of the earth, i e. for some 4.5 billion years. They are perhaps the most frightening and destructive phenomena of nature which man has to suffer. Until the last century man meekly put up with this scourge. Today we seem to be on the threshold of meeting the challenge, in part at least. We know by now where earthquakes are most likely to occur, how far we could anticipate them and act rationally so that the damage to life and property is reduced.

We now recognise that they are caused by the movement of the crust in response to the internal tectonic forces. The plates, or segments of the crust, which we discussed earlier, are constantly pushed around by internal forces and where the crust is weak it yields to these forces by disruption of the surface, expressed as an earthquake.

There are several causes, some very obvious and sufficiently proved, others only postulated. Global research is going on and we are moving forward every day. The interior of the earth holds the key. We have some idea of it from the volcanoes which bring up the magma. Had it not been for the volcanoes we should not have known much of the interior of the earth directly. Volcanic eruptions are often accompanied by earthquakes. But as stated earlier earthquakes can occur unassociated with volcanic activity.

There appears to be some truth in the belief that the position of the planets, with respect to the earth, can have an effect upon the earth's crust and for some distance below. As the moon influences the earth visibly, so far as it creates the tides, and invisibly as it affects the solid parts, — the earth also influences the Moon and other astral bodies reciprocally. Moonquakes (French 1977) which are already being monitored from the Earth, also show some correlation with the position of the Earth and the other planets. Through the gravitational pulls, different planets do affect each other reciprocally. According to Gribbon and Plagemann in the Jupiter effect (Gribbon & Plagemann 1975). 'When some other planet (Venus, Earth or Jupiter) is on

the same side of the Sun as Mercury during Mercury's closest approach to the Sun (perihelion), the Mercury effect is twice as large as when the planet is on the opposite side of the sun'. However, changes in gravity are not likely by themselves to generate earthquakes of any significant magnitude.

Some attention is now being directed by Soviet scientists, as well as others, to the study of eclipses and earthquakes. Kilston and Knopoff (1983) in their study of the Californian earthquake (Lunar-solar periodicities) (1983) record that "a search for tidal effects associated with these periodicities shows that large earthquakes have significant correlations with the times and orientations of daily or semi-daily tidal stresses, while the lunar fortnightly term is associated with the ocean tides along the southern Californian Coast". They further add, ".... at times near full or new moon, and near sunrise or sunset, one might be more likely than at other times to observe one or more large earthquakes in southern California." However, much more data would be necessary before this can be accepted as a hypothesis.

Various other reasons are pointed out for the generation of earthquakes. Natural gravity is one ubiquitous cause which is the fundamental law of the universe. If land masses can fall or move along the force of gravity, they will. If the movement is minor it may not be noticed, but if it is of a significant magnitude it may give rise to earthquakes or severe local ground shakes.

Magnitude and Intensity

Earthquakes are described or graded principally by the damage they cause. Even when they strike at places where no damage to life or property results, they cause deformity on the surface and need to be classified. The nature of the ground movement is by far the best criterion on which this classification may be based. Two parameters are considered, magnitude and intensity.

Magnitude is an absolute measurement, which can be determined with the help of instruments. Intensity on the other hand depends upon effects measured in quantitative terms and based largely upon field observations. Magnitude is expressed in Arabic numbers whereas intensity, for purposes of distinction, is expressed in Roman numerals.

Richter was one of the scientists who, in 1930, prepared an earthquake catalogue. Richter set himself to rank the size of the quakes into small, medium and large, based upon the instrumental determination of the effects. Since two different earthquakes originating at the same depth can cause dissimilar effects on the surface, the dissimilarity may be attributed to the difference in the amount of energy released at these two focal points. Thus the magnitude, related directly to the release of energy, is based upon the amount of energy released, measured instrumentally. Standard seismographs of the Wood-Anderson type are employed for this classification. The Richter scale is based upon the logarithm of the maximum amplitude recorded on the standard seismograph. Each unit of the scale rises by a ten-fold increase in amplitude.

Since the scale of magnitude is logarithmic, a rise of one digit of magnitude corresponds to a ten-fold increase in magnitude. The energy output increase about 30 times. The energy of an 8.6 magnitude earthquake, such as the 1964 Alaskan earthquake, is not merely twice as large as that in a shock of magnitude 4.3. The magnitude 8.6 quake releases almost a million times as much energy as one of magnitude 4.3. The scale is open at both ends in the sense that the smallest earthquake so far detected by the most sensitive seismographs is about 2 or slightly less while the highest magnitude recorded so far is about 8.9. It is visualised that we may come across quakes of smaller magnitude than 2 or larger than 8.9. Only two or three earthquakes so far have shown a magnitude of 8.9, like the January 1906, earthquake of Colombia-Equador and that of March 1933 in Japan. The San Fransisco earthquake of 1906 had the magnitude of 8.25; the Chilean earthquake of 1960 and the Alaskan earthquake of 1964 were both of M 8.5.

Earthquakes release varying amounts of energy, a part of which is expended in deforming the rocks above the focus and in causing ruptures and faults in them. The excess energy left after creating these changes is released at the surface. About 100 joules of energy are released/m^3 of rock involved in an earthquake. A 10^{16} m^3 mass of rocks involved in an earthquake may release energy, equivalent to an explosion of a thousand megatons of TNT. It is estimated that the energy released during a quake of magnitude 7 will be equal to the energy released by the two nuclear bombs dropped on Hiroshima and Nagasaki. Similarly, a 6.8 magnitude earthquake could power a city of 100,000 inhabitants, according to Clark (1984), for a year. A monster quake of 8.75 could keep that same city running for over 600 years.

Intensity on the other hand refers to the effects on human beings, their civilisation, structures etc. as determined by observing the effects on the society. The severity of these effects will depend upon the magnitude, focal depth, distance from the epicentre, geological conditions, type of construction etc. While magnitude may be the same for

two different earthquakes their intensity may differ widely.

In 1883, Rossi-Forel proposed a scale of intensity of ten levels in rising order of damage. Beginning with I, signifying only minor micro-seismic tremors, it would rise to V for a shock of moderate intensity and culminate in XII to signify a shock of extreme intensity. Mercalli in 1931 suggested a Modified Mercalli (MM) scale of intensity which was further revised in 1956 (table 3).

Table 3 *Modified Mercalli Intensity Scale of 1931 (1956 Version Abridged and Rewritten): Extracts*

Intensity	Description
I	Not felt, marginal and long-period effects of large earthquakes
III	Felt indoors. Hanging objects swing. Vibrations like passing of light trucks. Duration estimated. May not be recognised as an earthquake
V	Felt outdoors, direction estimated. Sleepers awakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move. Pendulam clocks stop, start, change rate
VII	Difficult to stand. Noticed by drivers of motor cars. Hanging objects quiver. Furniture broken. Damage to masonry, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices (also unbraced parapets and architectural ornaments — CFR). Waves on ponds, water turbid with mud. Small slides and caving-in along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged.
IX	General panic. Sometimes with complete collapse, masonry seriously damaged. (General damage to foundations—CFR). Frame structures, if not bolted, shifted off foundations. Frames cracked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluvial areas sand and mud ejected, earthquake fountains, sand craters
X	Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dykes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly
XII	Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air

It will be clear that the intensity will attenuate or diminish with increasing distance from the epicentre. To indicate the damage, lines of equal intensity or equal damage are drawn on the map (figure 1). These isoseismal maps are drawn for all earthquakes.

Great earthquakes of magnitude exceeding 8 occur once in every couple of years or so. The way in which two earthquakes of nearly similar magnitude may result in different intensity, can be easily demonstrated by examples of two earthquakes—the Kangra quakes of 1905 of 8.0 magnitude which killed over 20,000 people and the Kutch (Gujarat) earthquake of 1819, also of 8.3 magnitude, which killed no more than 1500.

Earthquakes are graded in terms of their magnitude. The frequency of these, based on the historical data, is also estimated.

Table 4 *Earthquake magnitude (M) and annual frequency*

Description	Magnitude	Annual Frequency
Great	8	1
Major	7 - 7.9	18
Large (destructive)	6 - 6.9	120
Moderate (damaging)	5 - 5.9	1000
Minor (damage slight)	4 - 4.9	6000
Generally felt	3 - 3.9	49000
Potentially perceptible	2 - 2.9	300000
Microearthquakes (imperceptible)	<2	

Source: *Earthquake Information Bulletin* **2** 26 (1970)

As could be seen from table 4, the number of minor earthquakes has been indeed very large. Above magnitude 6 there are about 120 and above M 7, about 18 earthquakes per year. Severe earthquakes above M 8 are only about 1 per year. This is only a general guide. The factual data differ appreciably from year to year and from country to country.

Extent of Movement

The total area over which the effects of an earthquake are visible can be established by a detailed survey of the area. The depth of focus is accurately determined by instruments operating from different networks. Several theoretical considerations are involved in arriving at a final decision. Thus the estimates of depth can be checked by observations in different seismic stations all over the Globe.

It would be interesting to make an estimate of the total volume of the rock-mass involved in any major earthquakes. One of the notable earthquake-affected areas was in Alaska where the earthquake of March 1964 was of magnitude 8.5. The area affected in the Alaska Earthquake (M 8.5) March 27, 1964 was, according to Berlin (1976), between 170,000 and 200,000 sq km, extending over 800 km by 250 km (200,000 sq km). This area was uplifted by 2-10 m on land and 15 m on the sea floor. The total uplifted area was between 60,000 and 90,000 sq km. An area of some 110,000 sq km subsided by about 1 m on the average. The focus was estimated at a depth of some 40 km. Thus the total volume of the rock-mass affected was nearly 8 million km^3.

The Assam earthquake of August 1950 (magnitude 8.5) lasted for about 4 min and affected an area of about one million cubic kilometres. As a result of the disturbance some 600 million cubic metres of clay were thrown out, while an area of about 1200 sq km is reported to have subsided. The focus was estimated at a depth of about 20 km. Thus about 20 million km^3 are estimated to have been affected in the earthquake.

The movement of such colossal volumes of rock masses, whether in vertical or lateral directions, must need an equally formidable source of energy. However, this is only a small part of the energy that the mantle exhibits in movements of the plates.

Prewarnings or Precursors of Earthquakes

Not all earthquakes are destructive to the same degree. In areas where they are expected and watched for, they cause less damage because of the awareness and the preparedness, however inadequate, of the people. The object of earthquake studies is ultimately to develop a technique by which the society suffers the least damage. The science of seismology should provide answers to such questions as, Can we anticipate earthquakes in good time? Can we defuse them or reduce their severity by any means?

The essential pre-requisites are that we study the earliest signs and symptoms of earthquakes. Considering that millions of cubic kilometres of earth's crust are violently rocked at the focal point and at the epicentre, the provocation for such movement must also be of a colossal magnitude. We at present do not, or cannot, know details of these provocations beyond saying that convection currents in the mantle cause earthquakes. But that is begging the question. What causes these currents, and how can we know more about them? That is the present enigma facing the science of seismology. If we realise this, we shall have realised our limitations in predicting earthquakes.

Earthquakes are a culminating point of certain internal processes of the earth. These processes are not necessarily spasmodic but often develop in a steady, systematic manner like a flower springing up from the bud. The emergence of a flower appears as a sudden phenomenon, yet is only one stage in the process of a plant's growth. In a similar manner an earthquake is an event in the internal process of the earth. It is its cataclysmic nature and unheralded arrival that frighten us because we are not fully aware of the intervening stages. We must attempt to understand these precursor events so that we can anticipate when the event will occur.

While the building up of an earthquake appears to be a simple physical phenomenon, it has several manifestations. The huge rock mass is being stressed gradually but inexorably from below. The pile of rocks between the focus and the epicentre, extending laterally to unpredictable distances, is being energised from below. In response, the rocks are deformed in spite of the internal resistance to the deformation. A time comes when the rocks cannot accommodate the deformation by adjusting the resistance within themselves, and they burst in the form of an earthquake. This deformation is compared to the stretching of a bow-string, or the elastic of a catapult, and suddenly releasing it. The longer the stretch of the bow or the catapult, the greater is the potential energy generated at the culminating point and the further will fly the arrow from the bow or the stone from the catapult.

The rocks behave in a similar manner. In accommodating the emerging energy the rocks will tend to show signs of disturbance. Before the earthquake waves emanating from the focus reach the surface, prior indications are seen or felt. Many physical phenomena occur such as folding and faulting, dilatance, tilting of the surface, production of gases from the mineral components of rocks, change in the velocity of the seismic waves, changes in earth's magnetic and electric fields, changes in the groundwater flow or levels in wells. Due to dilatance and bulging the gravity values of the earth will change.

There are numerous aspects of earthquakes in which people have interested themselves. the present report intends to focus attention on the neglected aspect of anomalous animal behaviour before earthquakes. If wisely interpreted, this behaviour can serve as a precursor no less reliable than any other geophysical precursors.

Precursors of Earthquakes

Physical

(A) Seismic
- (a) Change of velocities of P and S waves
- (b) Ratio of Vp/Vs
- (c) b-values, fore-shocks/after-shocks
- (d) Repetition of cycles
- (e) Microseismicity
- (f) Trend of previous shocks
- (g) Seismic gaps
- (h) Induced seismicity

(B) Geodetic
- (a) Land deformation (uplift & subsidence)
- (b) Fault displacement, creep
- (c) Dilatance, crustal deformation, change in gravity
- (d) Tilt and strain
- (e) Tides, and lunar tides
- (f) Bore-hole measurements
- (g) Changes in porosity and permeability
- (h) Fluctuation in oil production
- (i) Variation in ground and atmospheric temperature

(C) Electric and Electromagnetic
- (a) Change in resistivity of rocks
- (b) Dipole-Dipole methods, variometers
- (c) Laser Ranging
- (d) Changes in telluric currents
- (e) Changes in Earth's magnetic field
- (f) Ionisation
- (g) Emanation of aerosol particles
- (h) Unusual sudden change in weather

(D) Vibrations
- (a) Ground tremors (micro and macro)
- (b) Unusual sounds (infra, ultra) Acoustic emission
- (c) Changes in air pressure

(E) Odour (smell)
- (a) Emanation of unusual smell and odour
- (b) Emanation of gases

(F) Groundwater
- (a) Sudden change in water levels in lakes and wells
- (b) Emanation of Radon and other gases, bubbling
- (c) Mud and sand overflow to surface
- (d) Increase in salinity and other salts
- (e) Sea advance/retreat

(G) Astronomical
- (a) Astronomical effects of Sun, Moon and other planets and stars, eclipses etc.
- (b) Astrological implications

(H) Remote Sensing

Geodetic changes, measured by VLBI (Very Long Baseline Interferometry)

Biological

(A) Animal Behaviour
(B) Plant Behaviour
(C) Human Behaviour

Physical Precursors

Upheavel and Subsidence

The most ubiquitous symptom of an approaching earthquake is the effect on the land surface especially in the epicentral region. This surface shows changes in levels, with gradual, almost imperceptible, upheaval or subsidence. One example will illustrate the point. For about 60 years, according to Bolt (1978), a steady uplift and subsidence of the coast-line of Niigata, Honshu, Japan, was taking place. This rate slowed at the end of 1950's, but on June 16, 1964 a sudden subsidence of more than 20 cm was detected adjacent to the epicentre. This pattern of a possible precursor was discovered only after the earthquake that followed.

An area intercepted by faults is a place where the changes on the land surface can be easily detected. Along the San Andreas Fault the relative displacement reached 3.2 m in the 50 years before 1906. After 18 April, 1906 the relative displacement along the fault was 6.5 m. Some scientists, placing implicit faith in this one precursor alone, would rush to predict an earthquake. We cannot predict the elastic limit of a fault system, its ability to sustain strain without rupture. While faults are likely places where continuing strain can result in displacement and perhaps an earthquake, several faults have remained quiescent for centuries. However, the potentialities of displacement along faults cannot be ignored. When the energy is released through a fault the rupture can develop with a velocity of two or three kilometre per second!

The land level changes in Alaska consisted of (i) a zone of subsidence by almost 2 m, (ii) a zone of uplift on the seaword side, and (iii) a zone of uplift on the landward side. The maximum uplift recorded was 11 m in some places. It is found that even along a fault the release of energy is not continuous. There is a slip or creep at one point along the fault, while at other points the two sides

may remain locked up for a long time until sufficient energy builds up to tear them apart.

Tilt and Strain

Tilting of the Earth's surface is a common phenomenon in regions where earthquakes are building up. A measure of tilt is obviously a sure indication of stresses operating from below. A tilt-meter is designed to indicate and record the angle and the direction of tilt. If it is placed on the surface, the tilt is likely to be influenced by surface disturbances. Therefore, tilt-meters are usually palced in bore-holes sufficiently deep, to avoid surface disturbances, not connected with an earthquake. Japan's NRCDP have specialised in tilt-meters as well as the technique of improving bore-holes and down-hole installation of the meters.

A tilt-meter is essentially a pendulam-based instrument lowered to about 100 m. The measurable range is ± 200 micro-radians and the resolution is 0.006 micro-radians. This sensitivity, incidentally, can also detect the effects of tides.

One of the simplest device that we can depend upon as a tilt-meter is the inland lakes. Any tilt imparted to the ground will be reflected in the water level of the lake. This level will rise in the direction of the tilt and be depressed in the opposite direction. If some measuring poles are set up at the edges of lakes, the tilt will be apparent to even a casual observer. The rate of tilting can also be measured from the records of observations.

Similar to tilt, strain is also measured in bore-holes. The instrument for this detects the dilatation component as well as the volumetric strain.

From the above has developed the Integrated Bore-hole Observation System (IBOS) comprising a three component strain-meter and a tilt-meter installed in one bore-hole (NRCDP).

For island areas like Japan, precariously located in the grip of plates, geophysical measurements are a life-line for prediction or earthquakes. Not content with sensitive seismometer arrays on land, the Japanese (NRCDP) have developed a pop-up Ocean Bottom Seismometer (OBS) system.

For a country like Japan off-shore seismometers are indeed a boon, since they receive signals from far-off areas, enabling observers to refine their ability to predict on-coming events earlier than in land-locked areas.

Dilatancy

This is based upon the anomalous behaviour of rocks approaching the critical fracturing point. The velocity ratio between P waves and S waves (Vp/Vs) decreases initially because of the production of fractures in the rock and the consequent increase in volume of the rock mass near the epicentral region or the crown of the bulge. This is followed by a stage where velocities return to normal, a little before the earthquake. This lull in the velocities just before the catastrophe can form a useful precursor. In the dilatancy-diffusion hypothesis, it is water flowing into the cracked region before the earthquake, which causes the velocity ratio to return to normal. The increase in water pressure also serves to weaken the rock. If properly interpreted, this can serve as a significant precursor.

Micro-earthquakes or Microseism

Crustal adjustment also takes place in minor shocks called microseisms. The pattern of these microseisms and the fore-shocks also gives clues to the next earthquake. To detect these shocks, several kinds of seismographs are used, both on land and on the sea bottom. The off-shore seismographs are connected with the shore by cables over a distance of a hundred or two hundred kilometres.

Most seismic regions produce micro-earthquakes or imperceptible tremors which are occasionally followed by regular earthquakes. The incidence of these micro-earthquakes, which are of small magnitude and sometimes not easily measurable by seismographs, gives some indication of the seismicity of the region.

The incidence of micro-earthquakes increases about 8 times when the magnitude is lowered by 1. So by studying the pattern of micro-earthquakes we can know the pattern of seismicity in the area. For detecting very small earthquakes sensitive seismographs are necessary. A very dense and sensitive seismograph network is needed for monitoring the wide range of earthquakes. Even Japan has to be content with heavy arrays of instruments in only small parts of the country and in areas selected by the National Research Centre for Disaster Prevention (NRCDP). According to them about 60 stations comprising sensitive seismographs and tilt-meters, are spread over an area of about 100,000 sq km. Before the Matsushiro earthquake of 1967, Berlin (1976) reports that between 1965 and the main shock, nearly 700,000 micro-earthquakes were recorded and that, without exception, they were clustered in the epicentral region. Out of these nearly 60,000 were strong enough to be felt and 400 were damaging. This forerunner pattern was successfully used for long-range warnings issued by the Japanese Government.

Changes in Seismic Wave Velocities

Velocities of seismic waves P and S, have been found to vary, in response to the earthquake build-up. Strain produced in a rock alters the rocks

character, with a consequent variation in the velocities of the two principle types of waves. This means that the time taken by both waves will also differ. According to Seminov, the longer the *Vp/Vs* minimum persists, the larger will be the magnitude of the ensuing earthquake. In one case there was a decrease in *Vp/Vs* of up to 13%, which returned to near normal just before the earthquake. The first earthquake prediction in U.S., using travel time, was made at Blue Mountain Lake in August 1973. It was observed that for about two weeks, the travel time ratio remained at a mean level of 1.73 but on July 30, t_s/t_p travel time dropped to 1.5 and remained at this level for the next two to three days. *Vp* decreased by 22% from the normal value of 5.9 to 4.6 km/sec. and *Vs* dropped by 12% from 3.4 to 3.0 km/sec. The large variation in P-wave velocity was attributed to the dilatancy occurring in the water-saturated rocks in the focal region.

In parts of Japan, especially near the metropolitan areas, it is considered expedient to know the velocities of S waves down to several kilometres. The velocities of S waves are measured using deep bore-holes going down to 3 km and anchoring in the basement. Velocities of P waves are measured through surface seismic method by creating explosions near the surface and measuring the time of return of the reflected waves through geophones.

Electrical Resistivity

It has been established, according to Berlin (1976), that as the compressive stress grows, the resistivity to induced electric current increases up to about half way to rupture. This is obvious in cases where the rocks are water-saturated. Thereafter, as the stress continues, the resistivity decreases and comes to normal, and the rupture takes place. Variometers are used to monitor these changes in electrical resistivity. A variometer uses either direct or alternating current. A dipole-dipole configuration is used. The distance between the poles ranges from 5 to 7 km. This separation ensures penetration of the same extent. At the receiving dipole the drop in voltage is recorded, which forms the measure of change in the resistivity of the earth where the rocks are under rising stress. In some cases the Wenner configuration, with four poles, is used for the same purpose. This configuration was used about 60 km south of Tokyo. It detected a change in resistivity before several earthquakes.

Thus a change in the earth's resistivity can be a precursor in cases where the change is conspicuous.

Abnormal Earth-currents

Abnormal earth currents have already been described. These currents are extremely feeble, of the order of 30-300 millivolts, which are generated as force-runners of an earthquake, sometimes several days before the event. In February 1975, reports Helmut Tribusch, the Chinese group in Pan Shan observed a marked change in measurements of ground currents. The peizo-electric effects of quartz and magnetite crystals are well known. The ionisation in the atmosphere is also recorded as a precursor of earthquakes.

Generation of Magnetism

Rocks under tension, about to break into an earthquake, likewise generate geomagnetic fields, i.e. tectonomagnetic effects. This phenomenon has been observed in many cases. Before the Alaska earthquake of March 1964, magnitude 8.5, the intensity of the geomagnetic field had increased by 100 gammas, about an hour before the earthquake took place.

Another similar phenomenon is the generation of piezo-magnetism. When the mineral magnetite is under uniaxial compression, magnetism is generated. The magnetism decreases in the direction of the compression and increases in the direction at right angles to the direction of stress. A network for monitoring geomagnetic effects has been maintained by the Stanford University in California since 1965. A recent array established in 1973 employs a proton-precision magnetometer network consisting of over a hundred stations. An indisputable piece of evidence, according to Berlin (1976), was found in the Hollister earthquake of November 1974. By now the phenomenon has been well established. However, how far it can be relied upon as a precursor, depends upon the collateral evidence.

Study of Active Faults

Perhaps the most sensitive areas on the surface of the earth are the regions of active faults. These are already disturbed and displaced areas and the sealing between their two segments is often not very strong, so that even the slightest provocation causes a fresh displacement along the fault plane. In general these faults give perhaps the earliest indication of earthquakes. Fixed points on either side of the fault will show relative displacement, both vertical and lateral, which can be measured accurately by optical means or by a laser beam. One of the best monitored faults is the San Andreas Fault in California.

Radon Emanations

Sometimes rocks under stress generate emanations of radon or similar gas from the soil or

water. Berlin (1976) records that the Soviet Union recognised this phenomenon for the first time in April 1966 during the Tashkent earthquake, when radon anomalies were detected from the soil and water. In the Tashkent earthquake of 1966 radon emanations increased for five years before the quake and then suddenly, one year before the shock, the radon exhalations levelled off. In several other countries, including China and Japan, the radon anomalies are being watched. The University of California at Los Angeles, and the United States Geological Survey, watch radon emanation by the Track-Etch Method, using di-electric film that is sensitive to alpha radiation. The sub-surface pore-pressure variations could be responsible for radon emanations. Wells and springs in earthquake-prone areas are being watched for radon emanation as a precursor. The repeated mention of this phenomenon in most of the text-books is probably responsible for the high hopes raised for this precursor.

Groundwater Fluctuations

Groundwater fluctuations are also noticed in several earthquakes. Such changes of levels can be attributed to (i) change in the porosity of rocks modifying pore-pressures, (ii) change in the permeability of rock to water, and (iii) the tilt mentioned earlier. It would be pertinent to observe here that merely watching the wells visually will not give scientifically useful data. Permanent instruments need to be set up and watched by trained observers. However, these observers need not be very highly qualified, provided the instruments are of modern type and preferably automatic. Thus while this precursor indicated by water level changes appears simple, its operation to ensure accurate and reliable observations in sufficiently large numbers to render them dependable for predictions, is not so easy.

Reports from the People's Republic of China make a special mention of conspicuous changes in water level in wells during the Hsintai earthquake of 1966. Water levels rose by 2 m in the epicentral regions while outside this region the levels were depressed. Berlin (1976) also reports that between 94 AD, the earliest observation of this phenomenon, and 1973, some 15 earthquakes indicated a rise or fall of water level of several metres in the epicentral region.

Antecedent to several earthquakes in Taiwan, the water level in the wells, according to Berlin again, dropped and then rose just before the earthquakes. In some instances, change in the temperature of well water was also observed.

Without suitable instrumentation monitoring of water level in wells is not as easy as may be supposed; reports based on mere hearsay are often misleading. During the Koyna earthquake there were reports of changes of levels which could not be verified. In one village, a certain man vouched that the water level of his well dropped by one metre. A few minutes later, his wife came and proved that there was no change in the level, since her rope with its bucket could still reach the water which it could not have done if the level had gone down. Reports are often unfounded and misleading. Therefore, China has trained thousands of non-scientists to mark the levels in wells. Reports from these people can be relied upon for purpose of prediction.

The regional rise of sub-soil water level sometimes causes uneven sinking of the foundations of houses, buildings, bridges etc. The rise of water level causes liquifaction of soft rocks, like sand and clay, and consequent tilting or sinking of civil structures. House collapses account for a larger number of deaths and injuries than any other effect of an earthquake.

Before some earthquakes, apart from the rise and fall of the water level in wells, an emanation of radon, ions of Na, Ca, Mg, SO_4, HCO_3, F and Cl are released. Gases like H_2, CO_2 are also released from soil or water. Other gases like He, Ar and CH_4 also have been known to issue from wells and from springs. According to R Sugisaki et al. (1984) at Byakko spring He : Ar and CH_4 : Ar ratios increased until March 1984 and dropped abruptly in July 1984. They showed minimum emanation in August 1984. An earthquake of M 6.8 occurred in Nagano prefecture on September 14, 1984.

The *p*H of well water also changes before an earthquake. In several cases well water is observed to turn muddy, change colour or become salty.

Oil and eathquakes

The same phenomenon may be observed in the production from oil wells, as noted by Arich and Merzer (1974) in the Gulf of Suez and Eilat between 1965 and 1973. Like production, pressure changes in two gas fields (Niushan and Chutochi) in Taiwan were observed before the earthquake (magnitude 6.75) in January 1964.

There are several instances of changes brought about by an earthquake in oil and gas fields, such as change of oil-gas ratio, well-head pressures, regime of production of oil, production from abandoned wells, etc. If this aspect is recognised by the oil-field managements, this may develop into a fairly dependable precursor.

Acoustic Emissions

The mechanics of changes within the rock which is under continuing stress are not yet very clear. All such rocks are subject to micro-movements which cause audible or sub-audible sounds, or sounds which can be detected only by sensitive instruments or some animals. The frequency and magnitude of such acoustic emissions were measured for rocks stressed triaxially. Kisslinger and Suzuki (1978) report that although the emission rate dropped, some small crackling continued. Temperature does not seem to have any effect on acoustic emission. The NRCDP of Japan used high frequency wide-band (1 Hz to 100 KHz) instruments for detecting minute acoustic emissions. The 1906 earthquake of San Francisco was distinctly preceded by sounds, the predominant audio signals being in the range of 40 to 70 Hz. The NRCDP (Japan) believes that high frequency radiation generated in stressed rocks is a fairly dependable precursor.

Sensitive instruments of high frequency and wide band (1 Hz to 100 KHz) capacity have been specially designed for the purpose of detecting such minute earthsounds or seismic emissions. These form a conspicuous array of elaborate instrumentation. Here again, the Japanese NRCDP think fit to instal these instruments at the bottom of 160 m. bore holes made specially for this purpose, or else on the sea floor for precisely the same reason, namely to avoid surface disturbance.

Anomalous Light Phenomena

As early as Benjamin Franklin's time, anomalous lights were noticed which 'illuminated the night sky' before or during an earthquake. 'Spectacular lights' brightening up the sky were noticed before a major earthquake in Turkey in 1975.

One of the theories sponsored for this phenomenon is that hydrocarbons covert to methane (Von Nostrand Encyclopedia 1976), which is capable of surviving the high pressures and temperatures deep within the earth. Methane escaping through faults in the ground catches up small grains of dirt and dust which collide, creating sparks that could ignite the methane and cause flames and explosions. This phenomenon is reported both prior to and during some earthquakes.

In 1960 a Japanese scientist succeeded in photographing these lights. Yutaka Yasui photographed about 18 sites out of 35 that emanated during earthquakes between 1965 and 1967. It was confirmed that these lights were neither meteors nor arcing power-lines, nor lightning. Yasui enumerates the properties of earthquake lights as follows: (i) Central luminous body is a hemisphere, diameter about 20–200 m. (ii) Luminescence follows earthquakes with a duration of 10 sec to 2 min. Lights are seen on summits of mountains, and (iii) Radio interference follows luminescence and is strongest in the 10 to 20 Kz range.

Dr James Byerlee of the USGS has proferred an explanation for eerie lights as consisting of 'probable coronal discharges causes by strong electrical fields', similar to the "St. Elmo's Fire" which is often noticed near masts of ships during electrical storms. Byerlee believes that 'Friction heat vaporises the water inside the rocks. Loose electrons, freed as the water vaporises, congregate within the insulated zone on the surface of the fault plane, creating a large electrical field which causes any ions in the atmosphere to accelerate and throw off photons which are seen as light'. The result, Byerlee says, is the eerie light accompanied by a rumbling in the earth.

Lockner et al. as reported by Plinder (1984) have proposed a mechanism which can produce earthquake lights (EQLS). This relies on generation of electricity through the boiling of water in heated rocks as in fault or shear zones. Quakes of M 6 or 7 are known to have been generated in this way at temperatures above 350°C.

Two Japanese seismologists, Torahiko Terada and Kinkiti Musya, collected information on some 1500 reports of lights from the Indu Peninsula earthquake which occurred in November 1930. Charles Davison described their findings in 1937, that in most cases the sky was lit up as if by sheet lightning. Most observers felt that the EQL persisted much longer than ordinary lightning. Beams and columns of light were seen at different places and were visible up to 75 km away from the epicentre.

As reported by Derr of the USGS (1977) Byerly postulates that a fault may generate enough heat to ignite a fire. It was noticed that trees near a fault which was activated during the earthquake of Sonora (US) in 1897, were set afire; similarly a landslide, during the Owens Valley (U.S.) earthquake of 1872, caused fires in the mountains.

The consensus of various scientists is that the EQLS are coronal discharges caused by strong electrical fields, resembling the St. Elmo's Fire. The colours of these lights are pale blue or white with reddish or orange tints.

Finally it must be remembered that these EQLS occur as flashes, and unless one has pre-warnings one cannot observe them fully or photograph them. Besides, people under the stress of an earthquake may given distorted versions of what they saw, or draw upon their imagination. There is a possibility that such phenomena can occur due to other causes

in atmospheric geophysics, and that they, at times, could be fallacious as precursors of earthquake.

Induced Seismicity

Cases in which a dam appears, when filled for the first time, to have given rise to earthquake tremors are rare. In such cases it is logical to suspect that the seismicity is induced by the extra load of water. The small number of such dams, where reliable records of supposedly induced seismicity are available, are given by Rikitake (1976).

Table 5 *Man-made lakes and induced earthquakes*

Dam	Height (m)	Volume (10^6M^3)	Impounding	Date of earthquake	M (max.)
Hoover (USA)	142	35,000	1935	1939	5.0
Monteynard (France)	130	275	1962	1963	4.9
Kariba (Rhodesia)	125	175,000	1958	1963	6.1
Kremasta (Greece)	147	4,750	1965	1966	6.2
Koyna (India)	103	2,780	1962	1967	6.4
Hsinfengkiang (China)	105	11,500	1959	1962	6.1

These dams form an insignificantly minor proportion of the innumerable dams which have existed for years all over the globe. However, these six dams are marked by a close relation between the loading of water and the emergence of tremors around the dams. Such a phenomeon is not associated with many large dams which have stood for half a century.

Rikitake (1976) mentions that Kremasta dam in Greece received many foreshocks 5 months after impounding, the main shock of 6.2 magnitude occurring in Februrary, 1966. He further quotes an example of seismomagnetic effect of stress induced changes in magnetisation of rocks by impounding of water. When the Talbingo Dam in Australia was filled, the total magnetic intensity decreased by 2 to 8 gammas.

Rikitake (1976) presumes that dams above 100 m in height are susceptible to induced seismicity. He also feels that the volume of water behind the dam is also of no consequence. Chinese seismologists agree with this analysis. Due to the load of water, some water percolates down and probably lubricates the junctions of rocks and thus causes internal movements leading to earthquakes.

The largest load created by man on the earth is Lake Kariba in East Africa which had well over 150 km^3 of water in 1958. The seismicity was first noticed in 1961 and correlated with the load of water. That seismicity is observed even today.

Guha (1982) quotes about 70 cases of induced seismicity all over the globe. The height of the dams cited by him varies from 15.2 m (Ghirni, India) to 285 m (Nurek, USSR). The seismicity ranges from M 2 (Cabin Creek, USA) to M 6.3 (Kremasta, Greece) with Koyna (India) of a slightly higher magnitude, M 6.4. The earliest indication of induced seismicity was shown by Mead (Hoover Dam), USA as early as 1936.

Many aspects of this phenomenon are yet uncertain. The load of water may possibly be a cause of induced seismicity; if so, the cause very possibly be a rise in pore-pressure and consequent reduction of effective stress necessary for crustal readjustment.

The seismicity of all these dams seldom attains dangerous limits. On an average their magnitude ranges between 4 and 5. Their focus is usually shallow and mostly below the dams themselves. Therefore, they do not seem to constitute any significant danger to the society unless the dam already lacks the strength to withstand shocks of this magnitude. However, such dams do constitute a potential hazard and therefore they are being studied with meticulous care. The main hazard to the dam arises from surface faulting, strong ground movement, high water waves in the reservoir, landslides in the vicinity, while in extreme cases the dam itself may burst with consequent flooding of down-stream areas, and consequent damage.

Since the average magnitude of induced seismicity does not exeed about 5, by providing some more acceleration due to gravity the danger to the dams can be minimised. Within the known plate boundaries and other seismic areas such a provision in construction is indispensable. In other areas, supposed to be aseismic, this provision is often not thought of. However, the discovery of induced seismicity has created a certain amount of scare, and no dams are now built without consideration of this possibility, however remote it may seem.

Paired Earthquakes

Sometimes two earthquakes strike in the same vicinity, their activities being apparently connected with almost the same focus. In Japan, an earthquake of magnitude 7 which rocked Ibaraki Prefecture in July 1982 was followed by another quake of magnitude 6 in February 1983. Earlier, an earthquake of M 7.2 in January 1895 was similarly

followed by another, of magnitude 8.5, in January 1896, both near Ibaraki. The time gap between the two pairs is about 90 years. It is strange that both pairs should have occurred in the same geographical region, Ibaraki Prefecture.

The history of earthquakes is in some respects stranger than fiction. William Bakun of the USGS and Thomas McEvilly of the University of California, Berkeley, have brought to light an astonishing feature of the Parkfield area, as reported by Clark (1984). The seismographs of three events, 1922, 1934 and 1966, for which records are available, are remarkably similar. 'They are so alike that if you lay them on top of each other, the fit is almost perfect'. Bill Elsworth, Chief of the Branch of Seismology in Menlo Park says. "The conclusion jumps at you—the same earthquake is occurring over and over". All the dates suggest that Parkfield earthquakes are periodic, with similar properties. We think we are looking at a characteristic earthquake that repeats. This discovery has earned Bakun (1985) the title, 'prophet of repeatability'.

The example of southern California is also quoted in this context. There is evidence of 10 major quakes about 150 years apart over the last 1500 years. The last one was in 1857 so the next should come by the end of the present century. Bakun adds 'we may even be overdue for it now'. This means that one could expect another earthquake to strike at any time between now and the year 2000.

Palaeoseismology

One of the precursors is connected with the historical study of the foreshocks or of displacements in the crust, such as faults. If geological history can throw any light on past events it would also help to predict events in the future. Kerry Sieh, of the California Institute of Technology, feels Heppenheimer (75, p. 43) that the Holocene formations do not get their due attention in this respect. The sediments of some 10,000 years have not been fully explored from this point of view. Sieh found that the Wallace Creek Trench, California region, along the fault, 128 metres of sediments had accummulated in approximately 3,700 years, while in another trench, 475 metres' thickness had taken some 13,250 years. In both cases the slip-rate of the fault was close to 3.5 cm per year. He could date past earthquakes in Pallett Creek in the neighbourhood of the San Andreas fault.

During the past 2000 yrs Sieh found evidence of some 10 earthquakes. The earthquakes break or interrupt the steady sequence of sedimentation. He collected samples of peat, and with carbon 14 dating he established the dates of interruptions due to earthquakes. Sieh dated the pre—1957 earthquakes at 260, 350, 590, 735, 845, 935, 1015, 1080, 1350, 1550, 1720, A.D. The accuracy was of the order of a few decades. In general he found that there was evidence of major earthquakes every 150 years or so.

Near New Charleston, Palaeoseismologist, Pradeep Talwani, of the University of South Carolina, found characteristic disturbances in the trenches he dug, indicating that the Charleston earthquake was not the first major earthquake there. Talwani estimates a recurrence interval for such earthquakes of 700 to 1000 years. John Kelleher et al. found that the west coast of Maxico had seen more than 40 earthquakes of M 6 or larger, during the 20th century alone, compared with only six for all of California. The seismic gaps also could be studied.

T.A. Heppenhiemer (75) of the National Science Foundation goes further when he says, 'It is even possible that palaeo-seismology will wax while prospects for imminent prediction wane. The term earthquake prediction will come to mean the fore-telling of earthquake magnitudes and locations with the timing known to no better accuracy than years or even decades'.

Plants as Tell-tales of Earthquakes

Even plant life can serve a similar purpose if only we study the evidence carefully. Wallace and La Marche (1979) describe trees as a very dependable source of information about fault movements that have occurred before the earliest history. Robert Page of the USGS also investigated the effects of the 1958 earthquake on trees along the Fairweather Fault in Alaska.

Earthquakes and surface ruptures along faults affect trees in several ways. Among direct effects are tilting, fracturing, twisting, felling or burial of trees under landslides triggered by earthquakes. Amongst the long-range effects are the changes in the growth rate due to the hydrological and topographical changes as well as to biological effects such as the death of neighbouring trees. These changes have striking effects on the growth of rings.

Bores were taken in the stems of trees showing the annual or temporal increments. Simultaneously the trees that were cut for logging were also studied carefully. The earthquakes showed their typical fingerprints upon the trees. Red-wood and Douglas firs were sampled because their life-span was several hundred years. The rings were examined from the outermost to the one nearest the centre.

Many trees that survived the 1906 earthquake of San Fransisco were examined. In some cases tilting and fracturing were noticed without any difficulty. In some conifers the leaning of the trees caused an acceleration of growth on the underside of the tree. This naturally caused asymmetrical growth of the

rings in the cross-section. The character of the wood also changed, with a thickening on the underside, contrasting with the undisturbed area before the earthquake.

A very systematic inclinaiton of the trees was noticed in the direction opposite to the direction of the wave front. In the case of faults, the trees that escaped falling down, showed splitting or tearing due to the earthquake. In some cases the tops of trees were sheared off. A 46 m tall tree was broken off at 10 m above the ground. The sheared top, which lay not far away, could be seen for many years. At the same time a new tuft was growing with unmistakable change in nature. Care must, however, be taken to differentiate the effects of storms, lightning, etc. Some trees were uprooted and fell on their side in the same direction.

Ground tilts and incipient faulting can be indicated by trees, especially where they are aligned as in a plantation. As the ground tilts or sags, the trees lean or bend out of alignment (*Indian Soc. of Earthquake Technology*, November 1984).

Two leaning Douglas fir trees about 200 and 220-years-old according to Wallace and La Marche (1979) were found to have tilted down the slope. If the tilt is related to fault movement, the events would have occurred about 120 to 150 years before the 1906 earthquake. The rings show a sudden change in growth, the rings on the underside of the trunk being comparatively wider.

In another study Gordon Jacoby (1979) of Colombia University suggests that severe earthquakes of M 7 and above may leave their signature on the trees growing along or close to the fault line. The faster the tree grows the wider are its rings. When trees are tilted, the dark wood forms on the downward side as the trees attempt to straighten. The direction in which the wave-front affects the trees, and the intensity with which this happens, control the change in the width of the growth rings.

Earthquakes were sometimes found to have given a spurt to the growth of trees : slow-growing trees began to grow faster. Another result of the earthquake was that the sea coast was raised, and trees, whose growth was stunted because of the saline sprays and constant brackish atmosphere from the seas, started growing in full swing since the new environment was favourable to their growth.

Plants likewise show peculiar reactions. If they have flowered, the flowers may wither suddenly; some plants may flower quickly, out of season; some crops like potato, yarrow and cabbage may also bloom out of season. Apricot trees have bloomed in winter. Micro-earthquake shocks have affected the annual rings of trees, and at the specific time of the year have imprinted a shock on the growth rings (Wallace 1979). The reactions of plants can be, although in rare cases, precursors of an on-coming earthquake. The best contribution of plants is that they help to date past earthquakes.

Earthquakes are believed to improve the fertility of soils. The American Indians believe in this and they greet the earthquakes with jubilation. Italians and Venezuelans also believe the same.

In Italy, Tributsch (1982) states, 'Unusually vigorous plant growth has not only been documented for the earthquake of 1808, but has been confirmed in historical reports for several earthquake events of previous centuries'.

Instrumentation in Seismology

By far the most versatile instrument in the field of seismology is the seismograph. This consists essentially of a suspended pendulum able to move freely, with devices to record on a plain paper the direction in which the ground moves and the amplitude of the movement. A sensitive device to record the time is also incorporated in it. Thus it gives all the information about the magnitude and frequency of seismic waves, with the exact time of the event. The time is synchronised with prominent seismic networks elsewhere in the world. In order to fix the exact location of the epicentre at least three stations are necessary, so that by drawing circles obtained from three locations the intersection point can be arrived at. There are several networks of seismographs in the world, and there is thus no difficulty in deciding the epicentre of any new earthquake, provided the time device is properly synchronised.

The most famous network is the World-Wide Standard Seismograph Network (WWSSN). This was established in about 1911. By now there are some 120 stations in the network, about 35 from the U.S. and 85 from 68 other world countries. Each seismograph brings out six seismograph daily relating to movements or tremors in north-south, east-west and vertical directions. This network was earlier operated by the U.S. Geological Survey alone, but since 1973 it has been managed by the USGS and the National Science Foundation (NSF) jointly. Besides the above mentioned, national seismic networks have also been established by various countries such as Canada, Japan, Mexico, Sweden, Soviet Union, China and India. The Chinese network consists of some 17 standard stations.

The distribution of stations is largely guided by the situation and nature of earthquake-prone areas. California, which is one of the most vulnerable

regions for seismicity, has a closer grid network. The state has some 132 stations, which is by far the highest density of instrumentation for such areas.

Here it may be noted that there are only about 4000 reliable seismographs in the world, of which 800 are in California alone. These seismographs require a formidable back-up of recording and data interpretation centres. Global data need to be processed simultaneously in order to provide proper conclusions. Compared with the vast areas of vulnerable plate boundaries, seismic gaps, rift valleys and other earthquake-prone areas, the number of 4000 seismographs is indeed miserably below the requirement. This means that several areas, in almost every country, are monitored inadequately or not at all. If all the vulnerable areas of the world which are populated, and thus pose an appreciable risk to human life, were to be instrumented on the pattern of California or certain areas in China and Japan, several thousands of such seismographs, and perhaps even improved models, would be necessary. In addition to seismorgraphs there is a variety of other equipment, which can monitor other precursors, thus complimenting the seismograph arrays. Till the task is fully done earthquake monitoring by reliable seismographs and an adequate network of ancillary instruments would amount to no more than a pretence that 'we are doing our best to save societies from the scorage of earthquake hazard'. We shall revert to this topic while considering the prediction of earthquakes.

In the U.S. the seismically most active state is Alaska. Prior to the 1964 Anchorage catastrophe (M 9.2), which was the second largest in the Western Hemisphere in this century (Clark 1984), and one of the most devastating, Alaska had had only two regularly operating seismograph stations! Alaska was then the least populated state of the Union; if an earthquake of this magnitude were to strike there today, the loss of life could be enormous.

Space Techniques

The movement of the earth's surface in the context of earthquakes, is usually so slow and minute that it is difficult to observe or record it. For example the wearing of rocks due to sun, rain, wind and frost is so small that it is not noticed at all. There are few instruments which can measure such minute changes. In the movements caused by building up earthquake movements, even the instruments themselves will move with the changes on the land surface. It is therefore essential that we should have reference points away from the influence of these movements. Again, the areas over which such changes take place are so large that it is well-nigh impossible to keep track of movements upon them. For instance the movement of plates, the rising of mountain chains like the Himalayas, Alps, Andes, Rockies etc. are so minute that standard geodetic techniques like triangulation and levelling are inadequate and more accurate methods are necessary, if these measurements are to guide us.

Geodesy is a study of the size and shape of the earth, the precise location of positions on the earth's surface, and the determination of earth's gravity and magnetic fields. We have now reached a stage when we can use satellites and radio stars (quasars) as reference points and take measurements of the location of such positions. By repeated measurements we can determine the trends and amplitude of movements. Movements as low as 1–2 cm/year, over distances of thousands of kilometres, can now be reliably measured and monitored, according to Global Geodynamics of the NASA.

LASER mechanisms are used to send pulses from the ground towards reflectors in space. The return signals indicate changes in the two-preselected ground points. Four retro-reflectors have been placed on the Moon by Apollo astronauts and by the Soviet unmanned Luna mission. Similarly, the Laser Geodynamic Satellite (LAGEOS), high altitude satellite orbiting the earth in 3 hr and 25 min, remains at an altitude of about 6000 km from the earth. The satellite has, according to Spall (1979), 426 retroreflectors on its 2 ft diameter surface. Due to its high altitude, it is not affected by the earth's atmospheric drag, radiation pressures, or even the earth's gravity. The LASER beam reflected back to the earth station is accurate within a few centimetres. The earth's plates move at the rate of some 3 to 5 cm/year^{-1} and even these movements are accurately recorded. The movements of the mountains and those caused by pre-earthquake build-ups are recorded with similar precision in the McDonald observatory of the University of Texas at Fort Davis.

Texas University has also developed mobile Laser laboratories which can cover a number of sites through LAGEOS to an accuracy of 3 cm in 100 km. In the Very Long Distance Base Line Radio Interferometry (VLBI), distant galaxies are used as reflectors, from different tracking stations on the Earth. By measuring the time-lag of reflected signals between two stations, the change in the position of objects can be calculated very accurately. At least two or more stations are required for simultaneous observation. A later development is that, instead of depending on weak quasars from

the galaxies, artificial quasars are sent from the Global Positioning System (GPS) satellite. When the scheme is in full operation there will be 24 satellites operating simultaneously. These GPS signals are 100,000 times stronger than quasar signals from the galaxies, and they record movement accurately with a variation of only 1 to 2 cm/ year^{-1}.

These innovations help us to measure exactly the movements of the plates and similar other land disturbances. What is even more interesting is that intra-plate movements are also monitored by these same methods. In the United States' intra-plate region where several earthquakes have taken place — such as near Boston. Massachusetts; Charleston South Carolina; and New Madrid, Missouri — a careful watch is maintained for indications of earthquakes. The VLBI measurements are made over a 4000 km base line between California and Massachusetts. As has been pointed out, the vulnerable plate boundaries are watched through close grid observations but the intra-plate regions are almost neglected. Consequently when an intra-plate earthquake strikes, the people are taken unawares and, as stated earlier, the loss of life and damage are greater.

This is perhaps the most accurate instrumentation applied in earthquake prediction science. However, it must be remembered that all these instruments indicate no more than a 'trend' of ground movements; they do not help directly in predicting the actual moment of an earthquake.

Evaluation of Precursors

A number of geophysical precursors have been recognised, all of which have been useful at some time or other, although none by itself is expected to help the prediction of earthquakes. The problem is how to know which precursor should take precedence at any given time and place. More often than not, false or untenable conclusions seem to hold away, and the pros and cons do not lead to any agreement regarding the prediction of earthquakes.

In 1976, a panel comprising experts from the Soviet Union, the People's Republic of China, and the U.S. took a hard look at the possibility of prediction on the basis of any one precursor or even a combination of known precursors. Some of the conclusions they arrived at are very pertinent and are summarised below:

"Some anomalous phenomena precursory to some earthquakes have been identified; these phenomena are complex and will need considerable efforts in the field and in the laboratory as also theoretical studies; much denser net works are mandatory if we are to base an effective prediction programme on them. Predictions should specify exact place and time, magnitude and the degree of probability. The present distribution of instrumentation and the interpretation of results do not permit socially useful prediction. An 'area of intensive study', as is proclaimed in Japan, should be adopted. We might succeed in prediction in about 10 years in well-instrumented areas; predictions by individual scientists should be backed by full evaluation by the scientific community; there will be unavoidable errors and false alarms, even the ultimate system may not be infallible; the rate of improvement in this science will depend upon the amount, rate and deployment of funding; a prediction possibility will be of little value if social response procedures are not formulated concurrently; development of an earthquake prediction programme, and upgrading of earthquake engineering design and construction, are complementary and equally necessary, and should be carried out at the same time".

All this is applicable even to-day. Tatsch (1977) has summarised all the foregoing when he says "The interpretation of Earth' seismicity is still bedevilled by contradictions and uncertainties."

Roles of Precursors Compared

As stated earlier, the internal physical and physiochemical disturbances express themselves on the surface in a variety of ways, such as dilatance, tilts, velocity changes of seismic waves, foreshocks and microseismicity earth currents and their variations, water level fluctuations, emission of gases, and surface displacements by faults. Which of these anomalies will be prominently noticed before an earthquake will depend upon the depth of the focus, the geological properties of the intervening rocks, and the amount and nature of the provocation or energy from within.

Some attempts have been made to assess which of these precursors are readily activated before or during various earthquakes. Rikitake (1979) reviewed some 391 cases of earthquakes in which the most effective precursors were particularly in evidence. A similar exercise was also attempted by Jai Krishna (1980) in a hundred cases, to ascertain which precursors play the most prominent roles and which may be helpful in attempting prediction. The following table is based on their studies.

Table 6 reflects only a few cases that have attracted the attention of observers. Numerous other indications may not have been recorded, or even have escaped attention. It would not surprising if future studies of this nature should show an

Table 6 *Role of precursor anomalies*

		Rikitake	Jai Krishna
R.	Land deformation (30), tilt and strain (89), tidal strain (2)	121 (30.9 p.c.)	
JK.	Space deformation		40
R.	Foreshocks (83), anomalous seismicity (14), frequency magnitude relationship (12), microseismicity (4)	113 (28.9 p.c.)	
JK.	Foreshocks and microtremors		31
R.	Ratio of velocities of P & S waves (50), *Vp/Vs* (19)	69 (17.6 p.c.)	
JK.	Velocity ratio of longitudinal to transverse waves		10
R.	Earth currents (17), change in resistivity (32) and conductivity (3), of rocks' geomagnetism (6)	58 (14.8 p.c.)	
JK.	Changes in electrical resistance and electromagnetic field		12
R.	Source mechanism (7), hypocentral migration (4) and fault creeps (2).	13 (3.3 p.c.)	
R.	Underground water (2), radon (12), oil flow (3)	17 (4.3 p.c.)	
JK.	Changes in radioactivity from radon		4
JK.	Other methods such as focal mechanism, fault creep, magnetic anamalies, changes in chemical composition of groundwater and anomalies in petroleum discharge		3
	No. of Samples	391	100

altogether different pattern. Since no two earthquakes are similar in their origin and character, it is doubtful whether such studies by themselves will guide the science of prediction in the immediate future.

Besides the precursors listed in table 6, there are many others which have indicated the building up of earthquakes such as ionisation, generation of aerosol particles, sudden changes in weather, unusual sounds (ascoustic emissions), emanation of other gases and odours, anomalous lights in the sky, and in particular, anomalous animal behaviour.

Nearly 80% of precursors are connected with land deformations, foreshocks, microseismism, change in velocities of seismic waves, generation of earth currents and magnetism, and movements along faults. All these require numerous sophisticated instruments arrayed in dense networks which involve colossal expenditure and manpower; they must be monitored day after day, year after year, since there is no knowing when they may begin to give indications of internal movements, including those which lead to earthquakes.

Notwithstanding the statistical balance in favour of land deformation, velocities of seismic waves, etc. Rikitake (1982) warns that "There is no guarantee, however, that earthquakes are always associated with dilatancy generation. As stated earlier, it has now become clear that there are many earthquakes that are not preceded by a change in Vp or Vp/Vs ratio. The idea that dilatancy model could be applied to almost all earthquakes should be put aside."

CHAPTER II — EARTHQUAKE PREDICTION

Systematic study of earthquakes dates from the time when it was first recognised that the causes lie mostly within the earth. It was also recognised that if the event could be anticipated, methods could be devised to reduce the damage to life and property. However, no progress was achieved beyond recording the dates and times of the quakes and the damage caused by them.

Astrological predictions of earthquakes have been in vogue for hundreds of years in countries like China, India and some western countries but they lack precision as regards place, time or magnitude. Out of hundreds of predictions or speculations, a small number came vaguely close to the result but few people took serious notice of them. The game goes on even today, with many journals and magazines bringing out 'prediction' almost every week. Any person, not connected with this game, who makes a speculation has equal chances of being as close to success as a reputed astrologer. Astrologers' speculations are usually so vague that most of them are able to claim that they had predicted the event and that it did take place at the time, place and manner indicated by them!

The concept of predicting earthquakes on the basis of scientific knowledge began in the early 1960's. William F. Brace and his colleagues at the Massachusetts Institute of Technology (Bolt 1980) propounded that earthquakes can be forecast from changes in the ground surface such as dilantance, a process of swelling of the ground, with other attendant phenomena. The resistivity of the rocks in the region, it was discovered, changed significantly. The seismic waves within the region also showed appreciable changes to a velocity either higher or lower. This represented the earliest progress of scientific earthquake prediction. By the late 1960's two Russian seismologists, A N Semenov and I L Narsesov, according to Frank Press (Bolt 1980), startled the seismological world with the idea that spectacular variation in the velocities of seismic waves had occurred just before the earthquakes of Tadzhikistan, Tashkent and Kamchatka.

The heaving of the ground in the potential earthquake zone was attributed to the generation of cracks in the rocks as a result of stress from below. Even the resistivity changes were attributed to the same phenomenon. It was further noted that if these cracks happened to get flooded with water, the resistivity of the same rocks changed still further. In addition, in some cases the dilatance also gave rise to the emanation of radio-active radon gas. The dilatance-diffusion theory was initially proposed by Nur of Stanford University in 1972 and was further substantiated by Scholz, Sykes and Aggarwal of the Colombia University in 1973.

These ideas were followed up by many scientists from U.S., U.S.S.R., China and Japan. The dilatance-diffusion theory gave rise to a spurt in observations. Closer studies revealed that dilatance increased the flow of water through the rocks and that gases like radon emanated in certain streams, rivers and wells. Levels of water in wells, streams and springs were raised or lowered. Sea-levels also changed significantly. Magnetic fluctuation came to be associated with on-coming earthquakes. By now a number of precursors are known to precede earthquakes, and many places are watched in several countries.

Various methods are current in this field of earthquake prediction. They are classified broadly as (i) statistical, (ii) geophysical, (iii) mechanical, (iv) thermal and (v) chemical. These methods are adopted globally with varying emphasis. In spite of all the progress we have made in the techniques of following these methods, we do not seem to have acquired the art and science of prediction with the desired precision. The possibility of animal behaviour adding to our ability to predict earthquakes has not so far been seriously considered.

Precise Location of Earthquakes

The precursors fall into eight classes excluding animal and plant behaviour, which we shall discuss later. All these precursors are carefully watched in many prospective areas of earthquakes, and predictions are based upon the interpretation of their progress.

The precise location of an impending earthquake is one of the most important elements of prediction. The concept of plate boundaries is a hazy one and is difficult to show accurately on the map or

on the ground. The alignment of the plate boundaries is generally known but the breadth of the region is not amenable to precise description.

A prediction which covers a wide expanse amounting to tens of thousands of sq. km, loses its social utility. Such a prediction may perhaps be acceptable if the epicente is in the sea or a desert area, or is associated with big mountain ranges. No one is likely to take much notice of such a prediction except the scientific community all over the world. The risk to the society in such cases is almost nil, except for navigation and marine life.

When prediction refers to land areas, especially populated areas where the risk from earthquakes is very great, the prediction assumes a paramount importance. In such a case the more precise the area indicated, the more attention and respect will the prediction win from the population likely to be affected.

One of the lacunae in the present range of earthquake prediction is that the area indicated is very large, extending to several thousand sq. km. Over this area the populated portion may be small, and hence the people there are likely to take a chance by ignoring the prediction.

Astrologers in particular mention a vague area 'north-east of such and such a place', which conveys nothing to the people who are likely to come within the purview of the prediction. However, if an earthquake does materalise anywhere in that direction, the astrologers claim success for their prediction. In the matter of time factor a similar escape is found.

Quite apart from the attraction of claiming success in prediction, it is yet uncertain, scientifically speaking, where exactly the focus of an earthquake, or its epicentre will lie. Today it is wellnigh impossible to be precise in predicting an earthquake within, say, 500 sq km, where people will feel concerned and arouse themselves to meet the eventuality in a concerted manner.

Indications of the building up a earthquakes are noticeable over vast areas, as in the case of California, the Himalayas or the Chinese and Japanese earthquake-prone regions. Only vague indications, based broadly on the trends of the precursors, can be given. As the vagueness of the precursors increases, the faith in prediction decreases.

It is agreed by most leading seismologists that it will take some more time before they are able to interpret the precursors so as to arrive at a reliably precise prediction. Precise location and time are the heart of prediction.

Precise Time Window

The principal aim of prediction is, of course, to forewarn the society so that the people can prepare themselves. Predictions covering a long period, perhaps of several years, are not found helpful. The menacing San Andreas fault, which has been marked as the candidate for the next earthquake in U.S. for the last 60 years and more, is still a threat and there is no knowing when it may actually burst. Almost all known precursors are in evidence in this part of California. If the prediction is made only an hour or so before the anticipated event, there may be no time to warn the people, or for people to react appropriately. Therefore, it is obvious that a prediction must have a reasonable time limit, which must be neither too long nor too short.

Predictions are classified in various ways in this respect. One classification is as follows:

(1) A preliminary prediction–many years ahead,
(2) Long-range prediction–a few years ahead,
(3) Short-range prediction–say, a year ahead,
(4) Immediate–only a week or a month ahead of the event.

In the case of plate boundary regions mentioned earlier, indications that an earthquake is building up at any particular geographic location, are known many years in advance. Arrays of suitable instrumentation are laid on, but the precise point of time of the burst still cannot be indicated.

Though precision instruments have been developed covering all aspects of seismology, not many of the plate-boundary areas are adequately provided with all the effective instrumentation. It is noteworthy that there are not more than about 4000 reliable seismographs in the whole world. One of the most closely instrumented areas, according to Bakun and Lindh (1985), is the Parkfield network in California. This comprises 50 strong-motion accelerographs designed to provide a direct measure of the velocity of ruptures, estimates of the history and amplitude of seismic slip along the rupture, information about the high frequency radiation and directivity effects; they also monitor the fault zones. This network is in addition to a range of tilt-meters, strain-meters, and the LASER mechanisms and the VLBI mentioned earlier. Very few other areas have received this meticulous attention. Judged by the fact that plate-boundary areas cover millions of sq. km. the present arrays of instrumentation, confined to small selected areas, are patently inadequate for predicting the on-coming events within a reasonably short time. Even rich and advanced countries with regions susceptible to earthquakes, like the U.S.A., China, Russia and Japan, have only small portions of their vulnerable areas adquately instrumented. This means that large tracts of vulnerable areas are

watched half-heartedly or not at all. This is a serious constraint on our ability to predict earthquakes with any certainty even in the interplate regions.

Again, any agency — government or social — must observe that utmost caution lest a false alarm be given. The danger from a false alarm is sometimes greater than that from the natural calamity occurring in its own time as an act of God. Even today many knowledgeable scientists would much rather keep quiet, even when they can make a reasonable prediction, lest Nature fails to bear them out and the quake does not occur after all. The terror of the quake creates panic, disruption in daily life and possible death.

Reliability or Confidence Level

The society needs to know how reliable the prediction is; whether it is a broad guess or based on scientific calculations, whether it is 100, 80 or 60% certain that the event will take place. The level of confidence should improve if the event is building up. If the prediction indicates a period of one year ahead, the reliability of the prediction should increase as time passes. But from the nature of things, this does not necessarily happen and the predictions have often been falsified. In consequence several seismologists would lose confidence as time advanced and would feel compelled, from some inner urge, to withdraw their predictions before creating panic in the society with consequent danger to life.

The game of prediction has so many constraints and pitfalls that some authorities such as Frank Press (op. cit) think that 'the side effects of prediction might be worse than the benefits' and are discourged from venturing into prediction unless they are thoroughly convinced on all scientific parameters. This is the case in plate boundary areas, areas of rising mountain chains or sinking trenches etc. which are marked with some precision. These earthquakes belts are linear and extend for thousands of sq. km., out of which only a fraction is instrumented adequately for scientific predictions to be based on them. If this is the inadequacy for marked areas of plate boundaries how much more difficult must it be for tackling intra-plate areas, which are equally large if not larger in expanse, and where earthquakes are liable to occur, and have been occurring, anywhere within them? Today these areas are more or less out of the ambit of prediction preparations, unless they possess prominent tectonic features like Rift Valleys and faults like the San Andreas.

We have mentioned the two parameters of time and reliability. If the public are to react intelligently to an announced prediction, these two have to be combined. One practical method of combining them has been shown by the Earthquake Council of Japan, which has issued the following classificaiton:

Time Window

A. An earthquake would occur within several hours' time (imminent).
B. An earthquake would occur within a few days' time.
C. An earthquake would occur within a period that is not exactly known, but not very long.

Degree of Reliability

X. Highly reliable
Y. Slightly less reliable
Z. Possible

Thus the earthquake prediction should be expressed as a combination of A, B or C with X, Y or Z. A combination of AX would require the public's immediate reaction—Red Alert—through taking cover in earthquake-proof shelters or coming out in the open to reduce injuries and deaths from falling houses and debris. The combination CZ would imply a general warning and a call for preparedness, should a further prediction ensue indicating a higher degree of probability or upgrading of the time window.

This model only emphasises that precise time and reliability are essential elements of earthquake prediction.

While it would be ideal to be able to predict earthquakes within a few months, a somewhat long-term prediction can also be of great help provided the reliability is a high order.

According to Williams (1984) long-term predictions of 10 to 12 years can be helpful in deciding whether it is safe to locate nuclear power plants, high-rise buildings, high dams or similar heavy structures in the area. They will also indicate what building codes it will be appropriate to adopt, from the point of view of the safety of structures.

Professor Bolt, Seismologist at Berkely, feels that the ability to forecast how much the ground will move (M) at any place is more important, in reducing earthquake losses, than prediction of the actual earthquakes.

Magnitude of the Event

One more parameter in prediction must necessarily be the magnitude of the impending earthquake. If the earthquake is going to be up to magnitude 4 or less, the society need not panic but should remain prepared for slight disturbances. But if the prediction is for a higher magnitude, the society may need to prepare itself more seriously or even agree to be evacuated if necessary. Evacuation would be

a colossal job, upsetting the peace, tranquility and socio-economic tenor of the society. If such a confirmed prediction turns out to be a false alarm, much loss of life and even property may be caused and the responsibility, moral and even legal, may rest on the heads of persons predicting the earthquake. The present knowledge of seismology, and the wide range of instruments pressed into action, in varying intensities and a wide range of arrays, do give us progressively more useful information. Besides, there is a global network of cooperation amongst different countries so that any new information that one country may come across is readily shared with other countries.

Prediction Withdrawn

Two classic examples are quoted by Srivastava (1983) in this connection. Based upon the abrupt changes in the velocity ratio of seismic waves, an earthquake of M 5 to 6 magnitude was predicted by Dr J H Whitcomb on 15 April 1976 in California "within the next 12 months". This received very wide publicity in California. However, very soon after, Dr Whitcomb found that the indications leading towards the catastrophe appeared to slacken; whereupon, realising the likely unhappy consequences, he boldly withdrew his prediction. The earthquake did not materialise.

The second case is that of Dr B T Brady of the U.S. Bureau of Mines, who also followed a cue from the seismicity indications in rocks, and predicted earthquakes for Peru in July 1981 and again in April 1982. This was discussed in scientific forums in October 1980. Not only the news media but even the political lobby and the President of Peru became involved, and the matter was considered with the utmost concern by the country. The scientists discussed the pros and cons. Earthquake activity of a mild order was experienced in Peru during the latter part of 1980 and the earlier part of 1981. However, Dr Brady later withdrew his predictions because instead of the indications mounting up, he thought they were attenuating.

John Filson, the head of Earthquake Studies at the USGS in Reston, visited the city of Lima, the target of prediction, to lend credence to the assurance of the U.S. National Earthquake Prediction Evaluation Council, that Brady's prediction would not come true. The lesson learned from Brady's prediction, according to Kerr (1984), is that the Office of the Foreign Disaster Assistance (OFDA) which had earlier supported the prediction, lost more face than Brady himself.

This is a warning for any individual or a Government-sponsored organisation entrusted with reviewing predictions, to be extremely cautious in announcing earthquake prediction, especially in urban areas where people concerned are apt to respond, with likely unfortunate consequences.

Such instances show a good deal of human courage both in prediction and in withdrawl; in prediction, because the scientist does feel that the precursors are in fact leading to the catastrophe and he would genuinely like to save human lives by warning in good time. Many young scientists rush into such speculations without much thought but simply with an eye on publicity. Only mature geoscientists dare to predict and, if the subsequent course of the precursors ceases to uphold them, withdraw their prediction also in the interest of the society at large. Both the above instances show a much greater courage in withdrawing the prediction than in originally making it.

The news media are most anxious to highlight such predictions because they have no responsibility and can always claim to have played up the matter in the public interest.

Although the precursors are established and known, their trends towards the event are not always watched as they should be, with a view to the issue any modification of the prediction if necessary.

Authentic Records of Predictions

The USGS maintain a file of earthquake predictions from various sources. They are presently interested in precise prediction as regards location, time, magnitude and probability such as most predictors claim. They do not consider predictions which are made known after the event.

As soon as a detailed prediction is received, the essential details, according to Hunter (1976), are fed into a computer storage and analysis programme. If the prediction is borne out, it receives a score based on six pieces of information, viz. year, month, day, time, location and size. The success score depends upon the correct parameters ranging from 0.00 for a complete miss, to 1.00 for a perfect hit.

At the moment, Hunter (1976) says, the file contains 171 predictions from 32 authors, none of whom has achieved a high enough rating to merit any sort of consideration. Interested parties are invited to participate in the programme by sending their predictions to the USGS. Only in this way will we be able to sift the genuine scientific prediction from the tall claim which is often published after the event.

Earthquake Prediction Awaits Maturity

Of all the precursors of earthquakes, no one single precursor has helped to predict an earthquake with

certainty. We are not yet clear about the order of reliability of these precursors for being considered as basis for prediction.

The depth of the focus from the surface is pertinent, since disturbances at greater depth tend to get attenuated. In shallow earthquakes there is little attenuation and hence some of the thrust of the energy is manifest on surface disturbances.

As stated earlier a few of the predictions made by astrologers or occultists appear to be matched by the event. Any earth movements in the nearby areas, even though occurring at times different from those predicted, of any magnitude whatever, are taken as demonstrating the success of their predictions, which are no better than hit or miss. Since a large number of them attempt predicting simultaneously, some one from among them is apt to come close to the event. But there is no repeatability; the same person is not successful in subsequent predictions.

A global effort in seismological prediction is being co-ordinated with zeal and enthusiasm. Yet as at present any successful prediction may be a matter of luck. Until such time as the same scientists or organisations predict successively a few earthquakes in a row, with precision.

A socially usefull prediction of earthquakes needs a precise geographical point within some 500 sq km, within a pecise time window of a week to a couple of months and with a degree of probability of 70 to 80%. Until we can achieve such standard of accuracy, prediction cannot be a socially profitable guidance.

Progress and Limitations

Seismology is beset by several impounderables and unknowns as stated earlier. The deepest foci of earthquakes have been estimated down to 700 km, yet the exact physical properties of the interior of the earth are not fully understood. The crust is the earth's last bastion for resisting the disturbances coming from below. The strength and competence of the crust rocks are not fully known.

In spite of all these imponderables, seismology has done well and the progress made during the last fifty years is creditable. Today no underground nuclear explosion, made anywhere in the world, will go unnoticed. The international seismological network and understanding, will immediately detect these explosions and pin-point their locations as also the magnitude of the explosions. This is no small achievement.

Some recent predictions have nominated an area of 10,000 sq. km. Even presuming the epicenter of the earthquake does confine itself to this area, it is too expansive an area to be fortified against the damage. Besides, the time window is also several years, which does not give a clue to the society as to when precisely to expect it.

The recent Mexico earthquake was indicated by a young geophysist, Arun Bapat of Pune who, in 1983, a possibility of an earthquake in Mexico of about M 8, and within an area of 10,000 sq km and within 'four years' that is in about 1987. The earthquake of M 8 did strike the region within about two years. While this is a laudable effort, if this prediction was given recognition and publicity it would not have helped save loss of life as the event still took them by surprise and unprepared. The Mexico region is a well known seismic region where earthquake are expected. We are progressing, though socially useful prediction is still away.

However, what has been achieved is dwarfed by the vast amount still to be achieved. Satisfactory prediction of earthquakes is yet far away and although we are progressing fast, the final goal still eludes us. AS Cinna Lomnitz puts it in his paper, 'the Physics and Metaphysics of eathquake prediction' describes the present state of prediction as "long term optimism and a short term skepticism — a practical feasibility yet a distant goal".

Science knows no bounds, and one day we shall be able to accomplish this difficult task of prediction. In the meantime, earthquakes still catch us napping whenever they strike. While awaiting further refinements in prediction, we cannot watch helplessly; we should explore all possible other avenues which can supplement our prediction strategy.

Animal behaviour is one such avenue. Animals are being watched in many countries to see if they can give clues to earthquakes. Many authentic sources have agreed that animals have in the past announced on-coming earthquakes and several lives have thus been saved.

Animal Behaviour as Precursor

Animal behaviour has been studied in the laboratories, and animal sensitivities confirmed through meticulous experimentation, by several workers such as Buskirk et al. (1981). They have concluded that "some animals are much more capable than humans of perceiving certain kinds of geophysical stimuli.....some birds and fishes are more sensitive than humans to sounds with frequencies below 40 Hz; pigeons, kangaroo — rats and codfish have keener hearing than humans in the sound range of 25 to 50 Hz; certain fish are sensitive to electrical field changes as small as 10^{-5} V/M; stimuli caused by release of gases from small cracks may well be perceived by some animals;

ions in the atmosphere afford a positive explanation of unusual animal behaviour prior to earthquakes; homing pigeons can be thrown off their course of flight by as small a change as 30 gammas' etc."

Several other workers have carried out similar studies and enriched the fund of information on animal behaviour as a precursor. It is beyon ' doubt that many animals with their acute natural sensitivities, and their sixth sense of which we have discovered so little, can and do behave abnormally. If we can distinguish between their different modes of behaviour, we can interpret the anomalous specific behaviour of each species as the precursor of an earthquake and as a warning of an imminent earthquake.

In this combination of animal behaviour with man's interpretation of it, there can obviously be some limitations and lapses. One limitation is that as we go away from the epicentre of the earthquake, the stimuli attenuate, and at some distance away there is probably no precursor left. Moreover, if an earthquake strikes during the day, animals are easily seen and observed, but at night, animal reactions are low and not normally visible.

Animal behaviour promises to be an additional tool to supplement our strategy to predict earthquakes. Its value is enhanced by the fact that our ability to predict from geophysical precursors alone, to the accuracy that is necessary to save life and property, is seriously circumscribed by our lack of full knowledge of the parameters responsible for earthquakes.

We do know, however, on the basis of geophysical instrumentation, where earthquakes are building up. Initially, the watch on animal behaviour can be concentrated on these very areas, because we shall then be watching and monitoring sure candidates for future earthquakes. Quite apart from these known vulnerable areas, the animal watch should form a permanent social disipline, a way of life for all, so that even in areas which are not earmarked as earthquake-prone, but where earthquakes do happen and will happen as has been made out for intraplate areas, people will read and heed the warning.

Modern instrumentation is expensive in many ways. Instruments are costly to buy and have to be manned and maintained, data have to be collected and processed day after day for years together. The present global instrumental spread is inadequate for a reliable prediction, and an early improvement seems very unlikely, since a panel comprising experts from USSR, China and U.S. has observed that "the present distribution of instrumentation and the interpretation of results do not permit socially useful prediction.....we might succeed in prediction in about 10 years in well-instrumented areas". That was the situation in 1976. From all recent accounts we do not seem to have progressed materially on this front.

It is not that our quality of instrumentation lacks the necessary precision, but that it is quantitatively inadequate for the task. Sufficient efforts are being put into this field by geophysicists and seismologists; but as emphasised on page 553 and indicated in figure 4, the basic premises on which our conclusions are based are inadequate, due to our ignorance of the exact nature of convection currents, the physical parameters of the mantle and the strength or competance of the surface rocks to a depth of say, 10 km, whose rupture signals the earthquakes. Seismologists have progressed a good deal but they are limited by the uncertainty of the relevant aspects. How long it will take to overcome these limitations is anybody's guess.

It would be prudent on our part to explore all avenues to achieve socially useful prediction. If this subject is taken serious note of by all concerned — scientists as well as Governments — we can improve the usefulness of our prediction.

Animals are ubiquitous, and so are the observers. Animals will not necessarily be domestic ones. In fact they should be free-range animals and preferably unexposed to the stimuli produced by earthquakes. As in China, a beginning has been made in the U.S. also 'a few hundred collaborators are in touch with the central office..... About 70 animal species are being watched as a part of Project Earthquake Watch'. By this method, Tributsch (1982) thinks, 'we could reasonably expect that valuable information about controversial earthquake signs could be collected considerably faster than now'.

China thinks that this is a reliable additional avenue or precursor for prediction — not a substitution. The information should percolate from the cities to the rural areas through the common media of newspapers, radio, television and through the teaching community. The larger number of people involved, the greater will be the efficacy of this as additional precursor. As China believes, the People's war against Earthquakes must be won'. And who but the People should win it?

Prediction of Weather and Earthquakes Compared

Prediction of earthquakes is often compared to the prediction of weather. A little closer examination of these two scientific activities will show the inherent difference between them.

Weather is a condition of the atmosphere, at any particular time, in terms of heat, pressure, wind

speed and direction, and moisture. The troposphere is the main part of the atmosphere where weather is generated. Weather is a function of latitude, temperature, prevailing winds, ocean currents, influence of mountains, nearness to the sea etc. It involves averages, totals and extremes, which go to form the weather pattern. All these parameters are now amenable to measurement, with unprecedented accuracy, round the clock and all over the globe. Since the whole world is directly concerned with some parameters of the weather, there is a global effort to record the details, interpret them, and share them with the neighbouring countries or the whole world in the interests of weather forecasting.

Several aspects of community life depend upon the weather, upon the knowledge of what it is going to be like in the next few hours. If for a city a storm is forecast at 8.0 PM and it arrives at 5.30 PM, a very large number of commuters will be victims. For the fishermen who risk their lives at sea, for airmen and sea navigators, for off-shore oil explorers, the weather is their lifeline. Many a drilling platform has succumbed to the vagaries of inclement weather at sea. For agriculture, prediction of weather is vital. All these workers depend heavily upon pre-intimation of the future course of the weather.

Weathermen have satellites and computers, at their service. Innumerable instruments are collecting data in every country. The challenge of weather forecasting is a universal game played jointly by all nations on their home grounds—a unique example of international cooperation through which the quality of forecasting is enriched. Weather phenomena repeat themselves annually. The weatherman has the advantage of a global picture. Therefore weather should be relatively easy to predict.

At Reading in England there is a European Centre for medium range forecasting. The best meteorologists from 17 countries, according to Shannon Brownlee (1985), use the biggest and fastest super computer—the American-built Cray X-MP—to produce global forecasts, three to ten days in advance. It is fantastic to realise that there is an atmospheric model of the whole globe. The National Meteorological Centre of the U.S., Cyber 205, which produces forecasts up to five days in advance, twice daily, is heavily relied upon. About 500 maps, together with reams of printout, are issued daily by this Centre.

It would be relevant here to examine the loss of life and injuries to persons, including those rendered homeless, due to other natural hazards such as sudden changes of weather and due to earthquakes. The United Nations have examined this aspect and compiled the following statistics:

Table 7 *Results of natural disasters between 1900 and 1976*

Particulars	Persons killed	Persons injured or left homeless
Earthquakes	2,662,165	28,894,657
Volcanic eruptions	128,058	337,931
Floods	1,287,645	175,220,220
Landslides	3,006	44,673
Avalanches	3,059	150
Cyclones	434,894	17,648,463
Hurricanes	18,513	1,197,535
Typhoons	34,103	5,437,054
Storms	7,110	3,432,641
Tornadoes	1,175	342,459
Total	4,579,728	232,555,783

Source: Disaster Prevention and Mitigation (1979)

If we compare the number of deaths and of persons injured or left homeless due to earthquakes, with the corresponding figures due to inclement weather (a natural hazard), we shall notice that the total loss of life due to earthquakes, between 1900 and 1970, amounted to 2,662,165 while persons injured or rendered homeless numbered 28,894,657. The same figures for floods, cyclones, hurricanes, typhoons, storms and tornadoes would be, all added together, deaths 1,789,505 and persons injured or rendered homeless 203,317,195. It will be easy to see that the loss of life figures are somewhat comparable (2,662,165 and 1,789,505) whereas those injured and rendered homeless due to weather hazard are over seven times as many as due to earthquakes.

The weather is yet unpredictable over a narrow period of time, even though its degree of intensity, may make all the difference between life and death for some people. As Brownlee quotes, "In February 1983, commuters headed home from Manhattan one evening, to a prediction of light dusting of snow. It snowed all night and by morning the city and nearby Long Island were immobilized under 17 inches of snow"!. During the night the centre of the storm shifted unexpectedly and immobilised Long Island which had counted on fine weather.

In some countries, neglect in forecasting attracts the provisions of law. The National Weather Service (NWS) neglected to repair one of their weather buoys. Consequently on 21 November 1980 they failed to warn the fishermen. A 100 mph wind and 60-foot waves lashed the fishing boats and four

fishermen perished. The District Judge, Joseph Tauro, ruled that the Government had neglected its duty to ensure that forecasts be as accurate as possible and had failed to warn fishermen that its predictions were based on incomplete data.

In spite of such lapses, tremendous progress has been made during the last 50 years in the science of weather forecasting. Yet the weather prediction can still mean the opposite of what it has said! Off-shore drilling platforms get a four-hourly weather forecast, and yet a number of platforms succumb to bad weather every year. The death toll from unpredicted floods, droughts, tornadoes, typhoons, hurricanes and tsunamis is so large, that one wonders whether we have truly mastered the art and science of weather forecasting.

If this is true of weather prediction, in which all the parameters can be measured accurately on the surface of the earth, round the clock and round the globe, what are our chances of predicting earthquakes precisely as regards space, time, magnitude and reliability, all at once, in the face of the numerous unknowns?

If the weatherman proves wrong — as he often does on closer scrutiny — nobody usually takes much notice of him. But if a seismologist's prediction for a city goes wrong, he will be sued — if he escapes lynching!

Animals as Weather Indicators

Many animals are known to be sensitive to on-coming severe weather changes. People who live on the banks of a river and are keen observers, have commonly noticed that birds build their nets higher up than usual on the trees if they anticipate high floods. In a sudden storm which developed along the coast, a large number of cattle, sheep and other domestic animals perished but, strangely enough, dogs were not among the victims. Obviously dogs, who outnumber some of the other species, got the scent of the on-coming storm and ran away to safety in good time. Rodents leave their hide-outs on the bank of a river just before floods. A list of animals behaviour before a dramatic change of weather is given in table 8.

However, it is noticed that the incidence of animal sensitivity to likely weather changes is much less, and less spectacular, than the anomalous animal behaviour before earthquakes. People who doubt the role of animal behaviour as a precursor of earthquakes, often ask, "Can animals not behave unusually in response to some other stimuli, like a sudden change of weather?" The reply is that the response to sudden weather change is not so spectacular as the response to an on-coming earthquake, because change of weather is an annual feature of which animals have previous experience, and therefore they can anticipate. Only in extreme cases do they show the startle response. Unlike weather changes, earthquakes are occurrences of which animals have little or no experiene; therefore, their reactions to quakes are very sudden, spontaneous and spectacular.

Table 8 *Comparison of unusual behaviour of animals before earthquakes and before dramatic weather changes*

Behaviour before bad weather	Behaviour before earthquakes	Ref. for earthquake behaviour
Aquatic birds leave inland lakes.	Waterbirds evacuate lake; swans and ducks leave water, refuse to return.	Montana, 1959 China, general rule
Birds are excited, flock together, fly this way and that.	Excited storks take to the air, chickens flock; fowls flutter excitedly; noisy birds fly up and circle excitedly; pigeons fly around without letup.	Sofiadhes & Greece 1954, Java 1867, Liguria 1887, Alaska 1958 China, general rule
Many birds have special rain or weather calls.	Remarkable and unusually timed calls; chickens cry, often constantly.	Peruvian folklore Friuli 1976 China, general rule
Cattle enter stalls late.	Cattle and pigs refuse to enter stalls, or flee from them.	China, general rule
	Pets try to flee outdoors.	Liguria 1887
Roe deer and other game leave the woods, lose shyness.	A herd of roe deer leaves forest and approaches the village. Wild animals lose shyness, approach people.	Friuli 1976
Insects change flight behaviour, fly close to ground and water.	Giant swarm of fire-flies flew close to the water.	Friuli 1976
	Insects form swarms.	Japanese popular belief

Source: When Snakes Awake (Tributsch 1982)

Initially a layman will get confused, but after some education and experience, will learn to distinguish how animal behaviour differs in the two different contexts. Table 8 gives the comparison between the unusual animal behaviour before the dramatic weather changes and before earthquakes, as brought out by Helmut Tributsch.