EARTHQUAKES:
Cause, Prediction, and Control

J. H. TATSCH

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An analysis of the cause, prediction, and control of earthquakes in terms of a single, long-lived, deep-seated, global driving mechanism that has been operating during the entire 4.6 billion years that the Earth is believed to have been in existence.

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Preface

One of the conclusions from the research that went into this book is that it is necessary to understand what causes earthquakes before attempting to predict and control them. Consequently, almost all of the book is devoted to an analysis of what causes earthquakes. This is done primarily by studying the known earthquakes in terms of those aspects of the Earth's behavior that appear to be related to earthquakes.

More specifically, this book attempts to relate the present earthquakes to the manifestations as well as to the vestiges of a single, long-lived, deep-seated global, mechanism that appears to have been operating within the Earth during the entire 4.6 billion years that the Earth is believed to have been in existence. This mechanism is the "tectonospheric Earth model," which has been described in the book, *The Earth's Tectonosphere,* and used as the basis for the books, *Mineral Deposits, Petroleum Deposits, Uranium Deposits, Geothermal Deposits,* and *Coal Deposits.*

The Tectonospheric Earth Model differs essentially from other global-tectonics concepts in two salient respects: (1) as above indicated, it embodies the geometrical, mechanical, thermal, and chemical aspects of a driving mechanism that has existed during the entire 4.6 billion years that the Earth is believed to have been in existence; and (2) it encompasses the Earth's spatio-temporal framework to a depth of 1000 kilometers during these 4.6 billion years. Thus, this concept pertains not only to the Earth's present lithospheric plates but to all plates, blocks, and other forms of material that have evolved within the upper 1000 kilometers of the Earth during the past 4.6 billion years.

It is the author's opinion that these two differences permit a more meaningful interpretation of the origin, evolution, and present characteristics of the Earth's seismic behavior than is possible through other global-tectonics concepts.

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Chapter 1

THE EARTH'S SEISMICITY: A GLOBAL SURVEY

Any analysis of the cause, prediction, and control of earthquakes faces a dichotomy. No one knows exactly what causes them. Yet, in order to effectively predict earthquakes, it is necessary to know what causes them. With this in mind, the major portion of this book is devoted to an analysis of the cause of earthquakes. Once the cause of earthquakes is known, then it should be a relatively simple matter to determine to what extent it may be possible to predict and control them.

Most researchers now agree that, although great strides have been made in recent earthquake research, the physical laws governing earthquake behavior are still inadequately understood (See, e. g., Borcherdt, 1975; Kisslinger, 1976; Press, 1976; Rikitake, 1976; Raleigh, 1977). Before considering the details of the applicalbe geometrical, mechanical, thermal, and chemical aspects of the Earth's behavior that appear to be related to the earthquake causal mechanism, it is well to take a brief look at the salient characteristics of the Earth's seismicity when viewed on a global scale.

Some Major Earthquakes.

Some of the Earth's most destructive earthquakes have included the following:

Year	Location	Deaths
342	Antakya, Turkey	40,000

565	Antakya, Turkey	30,000
856	Corinth, Greece	45,000
1201	Aegean Sea, Greece	100,000
1268	Seyhan, Turkey	60,000
1290	Jehol, China	100,000
1456	Naples, Italy	30,000
1556	Shansi, China	830,000
1622	Kansu, China	12,000
1641	Tabriz, Iran	30,000
1653	Izmir, Turkey	15,000
1667	Shemakha, Iran	80,000
1688	Izmir, Turkey	15,000
1715	Algiers, Algeria	20,000
1737	Bengal, India	300,000
1755	Lisbon, Portugal	60,000
1755	Kashan, Iran	40,000
1759	Sfat, Jordan	20,000
1783	Calabria, Italy	50,000
1847	Zenjosi, Japan	12,000
1853	Shiraz, Iran	12,000
1853	Isfahan, Iran	10,000
1861	Mendoza, Argentina	18,000
1896	Riku-Ugo, Japan	27,000
1905	Kangra, India	19,000
1908	Messina, Italy	83,000
1915	Avezzano, Italy	30,000
1920	Kansu, China	180,000
1923	Kwanto, Japan	140,000
1934	Bihar, India	11,000
1935	Quetta, Pakistan	30,000
1939	Chillan, Chile	30,000
1960	Agadir, Morocco	15,000
1968	Khorasan, Iran	13,000
1970	Ancash, Peru	40,000

1972	Ghir, Africa	17,000
1972	Managua, Nicaragua	23,000
1976	Tangshan, China	655,000

The Relationship between the Earth's Seismic and Dynamic Behavior.

Although the exact relationship between the Earth's seismic and dynamic behavior is not understood, the observed correlation between the two is such that any hypothesis for the evolution of the Earth's tectonosphere must account for those areas of seismic behavior that correlate with the dynamics of the tectonosphere. For example, strong tectonic activity is concentrated into a relatively few narrow belts, aggregating roughly 60,000 km (a distance roughly equivalent to about 1 1/2 global circumferences). Almost all present seismic and volcanic activity occurs within those segments of the mobile belts that comprise the oceanic and continental rift systems, the island-arc complexes, and the young fold belts.

These observations suggest that the narrow active belts are due to interactions between a relatively small number of very large blocks within the Earth's tectonosphere. Not understood is the cause of the concentration of material into such large blocks and the resulting localization of tectonic, magmatic, seismic, and metamorphic activity into long narrow belts that lie between the postulated blocks. Although the cause for such concentration is not understood, it suggests that the seismic belts are part of a single global system.

Fig. 1-1 shows the worldwide distribution pattern of the earthquakes. A study of the data upon which this figure is based (See, e. g., Barazangi and Dorman, 1969; ESSA, 1970) shows that the deeper earthquakes are restricted to narrow, more-or-less central portions of those belts that contain earthquakes at all depths. Where deep earthquakes do occur, the seismic activity is concentrated primarily along the edges of the lithospheric blocks.

Seismic Behavior as a Function of Tectonospheric Structure.

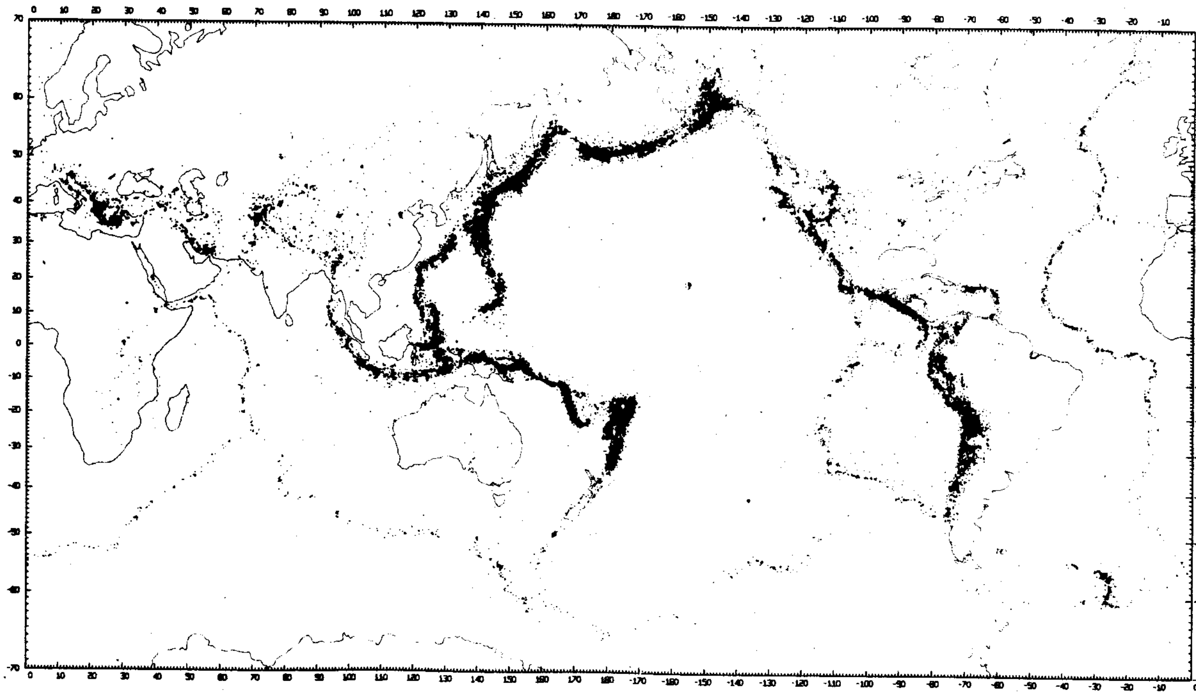

Fig. 1-1. Worldwide distribution of earthquakes. (Based on Barazangi and Dorman, 1969; ESSA, 1970).

Observational evidence suggests that, in both oceanic and continental areas, both the crust and the mantle are thinly stratified. Other studies indicate that, in addition to such vertical variations in structure, the tectonosphere contains horizontal variations in both the crust and the upper mantle. Although the oceanic crust is thinner than is the continental crust and differs in other respects, such differences do not extend into the upper mantle. Consequently, the upper mantle is approximately the same under both the oceanic and continental areas.

The Correlation of Seismic Behavior with Tectonomagmatic Activity.

It has been known for some time that seismic behavior correlates generally with certain tectonomagmatic activity when viewed on a global scale (See, e. g., Gutenberg and Richter, 1954; Holmes, 1965; Hart, 1969). In certain areas of the Earth, more specific correlations have been observed between (1) heat flow and seismic delay time; (2) alignments of seismic epicenters, gravity trends, and volcanoes; and (3) deep earthquakes, shallow earthquakes, and volcanism occurring in common structure.

In spite of these correlations, there are distinct cases of non-correlation. Some segments of the oceanic ridges are tectonically active but seismically inactive. Some volcanic segments are aseismic. Some highly seismic segments are not volcanic. Other highly seismic segments showing no tectonomagmatic activity (at least not at the Earth's surface) can be explained by seismic stress release and fracture at depth, without the occurrence of surficial fractures. But other non-correlations of seismic activity with tectonomagmatic activity are not so easily explained.

Seismic Behavior at Various Depths within the Tectonosphere.

In analyzing the Earth's seismic behavior, it is necessary to consider a complete spectrum of earthquake depths, ranging from the surface of the Earth to over 700 km into the tectonosphere. The problem is complicated by the differences observed in seismic behavior at various depths. For example, the upper mantle appears to attenuate S waves more than does the lower mantle; the difference amounts to an order of magnitude (Knopoff, 1969b). The upper mantle also can be separated into several layers, the lower layers having lower values of Q. Average values of Q from Knopoff's model are 120, from 0 to 325 km; 75, from 325 to 650 km; etc.

A study of the Earth's seismic behavior reveals that some shallow earthquakes are produced by the same mechanism that produces deep earthquakes. Those shallow earthquakes that do not have a common motivation with the deep earthquakes are probably produced by surficial activity such as (1) interactions between lithospheric plates, (2) gravitational sliding within the lithosphere, (3) volcanic activity, and (4) isostatic adjustments and certain other second-order activity near the surface of the Earth.

Not completely understood is the motivation for those shallow earthquakes that seem to share a causal mechanism with the deep earthquakes. Much work remains to be done in that area. The task is made more difficult by the paucity of deep earthquakes and by the in applicability of most physical concepts at depths of 700 km. Certain observations, if considered on a global basis, may, however, provide at least a tentative answer. These observations are considered in subsequent sections on hypotheses. Suffice it here to say merely that the deep-focus earthquakes are fewer in total number than are the shallower ones; they are more limited in geographical distribution; and they have more-complex energy distributions for their motivation.

The Regional Characteristics of the Earth's Seismicity.

Certain regions of the Earth show distinct seismic patterns. The two most conspicuous patterns are the Circum-Pacific belt and the Trans-Eurasian (of Tethyan) belt, lying orthogonal to each other. Segments of these belts are approximately great-circular arcs: 180° in length for the Trans-Eurasian belt and 270° for the Circum-Pacific belt, as shown in Fig. 1-2.

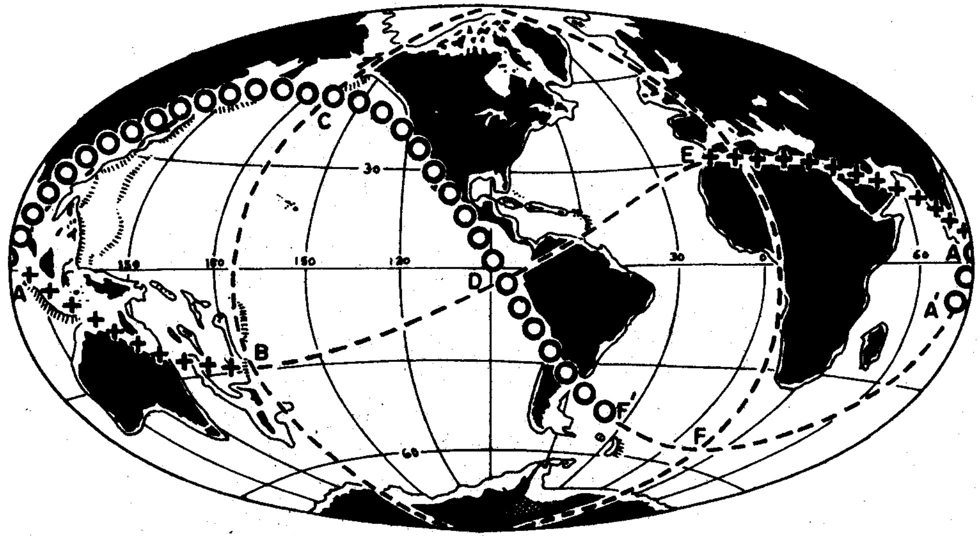

Fig. 1-2. The Circum-Pacific and Trans-Eurasian (Tethyan) seismic belts, superimposed upon a modified Aitoff projection of the Earth. See text for details. (Adapted by J. C. Holden from the author's sketch in Tatsch, 1972a).

The Trans-Eurasian (Tethyan) seismic belt, as usually defined, extends approximately along most of the great-circular segment, EAB, aggregating about 180° in length. The Circum-Pacific seismic belt, as usually defined, extends approximately along the great-circular segment A'ACDF', aggregating roughly 270° in length. These two belts are usually described as intersecting in the vininity of A. The Circum-Pacific seismic belt accounts for 75% of the earthquakke that have occurred within recorded history; the Trans-Eurasian (Tethyan) belt accounts forall except 2% of the remainder.

A close scrutiny of these bwo belts, which account for almost all of the Earth's present seismicity, should provide many details regarding tectonospheric dynamics. Any analysis of these two belts should note, for example, the relatively short-lived existence of the geographical features associated with them. Thus, because neither the Pacific Ocean nor the Tethyan zone has been in existence over a long period of time, one should suspect that the two seismic belts presently associated with these geographical features are also relatively short-lived.

Confirmation of the suspected short-lived existence of these and other regional seismic patterns may be found in the relationships existing between the Earth's seismic behavior and other geophenomena. It has long been suspected, for example, that the Earth's seismic behavior correlates with certain tectonomagmatic activity and that both are related to the deep structure and behavior of the Earth on a global scale (See, e. g., Hart, 1969; Drake, 1970, 1976). Most evidence indicates that tectonomagmatic activity has occurred in various parts of the Earth during at least a major portion of the past 4.6 b. y.

If the Earth's seismic behavior has always been associated with its tectonomagmatic activity, then both could be attributable to a single, deep-seated, global mechanism that has existed during a considerable portion of the Earth's life.

Low-Velocity Zones, High-Velocity Areas, and Other Seismic Anomalies.

In considering the Earth's seismic behavior, and its relationship to the evolution of the Earth's tectonosphere, it is well to include a brief analysis of the salient seismic anomalies within the tectonosphere. Most of these anomalies are related to seismic velocity gradients and are usually referred to as "low-velocity zones", "wave guides", "high-velocity areas", etc. Generally, the low-velocity zones correlate with areas that exhibit tectonomagmatic activity; high-velocity areas, with stable areas. Thus, low-velocity anomalies are usually associated with high-temperature, high-attenuation environments, whereas high-velocity anomalies are usually associated with low-temperature, low-attenuation environments within the tectonosphere. A study of seismic velocity anomalies, therefore, provides a means of evaluating some of the "fine-structure" characteristics of the tectonosphere.

The existence of low-velocity zones within the tectonosphere has been confirmed for both P and S waves in most tectonic configurations. The most-probable explanation for low-velocity zones appears to be some form of incipient melting within the tectonosphere (perhaps involving eclogite or peridotite in the presence of water).

The exact configuration of the low-velocity zone varies with the tectonic environment and probably coincides with a layer of reduced viscosity. Some evidence indicates that the low-veolcity zone may consist of several layers, one above the other (See, e. g., Beloussov, 1969).

Simple explanations for the cause of the melting in the tectonosphere to cause the low-velocity zone are not available (See, e, g., Ringwood, 1969); but it appears that the melting occurs where the geotherm rises above the dry solidus (Lambert and Wyllie, 1970). Unexplained is the limited vertical extent of the zone from 100 km to 250 km under continents; from 50 km to 400 km under the oceans. Also, the low-velocity zone may not be produced by the effects of high temperature alone (Tatsch, 1977a).

Seismic attenuation appears to correlate with low-velocity regions. Values are about 3 times higher in the semi-stable regions of the USA than they are in the Basin and Range province. Also, regions of low velocity are often areas of high heat flow, particularly on oceanic ridges and in analogous continental regions such as the Basin and Range province, where heat-flow values are well above the average.

There appears to be a correlation between regional variations in crustal thickness and the Earth's stress field (See, e. g., McBirney, 1969). Basically, the crust appears thinner than average beneath regions in tension (e. g., the Basin and Range province; "active" regions in both continental and oceanic areas; and oceanic ridges). On the other hand, it appears thicker than average under regions in compression (e. g., continental shields; ocean basins; the low-density "roots" of fold mountains; and the crust beneath the islands in island-arc complexes). Under the Kuril volcanic island-arc, a projection of the low-velocity zone reaches the base of the crust; lava flows through this projection to the volcanoes (See, e. g., Beloussov, 1969).

Liebermann and Schreiber (1969) found evidence that a low-velocity layer for S waves can exist without one for P waves and that the shear velocity may decrease with depth in the transition region of the mantle.

The tectonosphere displays a myriad of heterogeneities, and the wave behavior within heterogeneous material differs considerable from that within a homogeneous, idealized, non-stratified material without any pressure and temperature gradients. For example, one phenomenon that does not appear in homogeneous media is the interaction of P and S waves, such as is observed within heterogeneous material even in the absence of boundaries or discontinuities. Among other things, there is a conversion of P and S waves during propagation as well as during internal reflection. Also, higher degrees of heterogeneity cause a higher degree of conversion from P to S waves. Generally, low-velocity zones and other seismic anomalies appear to be related to physical parameters of the travel path, rather than solely to parameters of the environments at the source and receiving stations.

The Earth's Seismic Behavior According to the Elastic Rebound Hypothesis.

Many hypotheses have been developed in an attempt to explain the Earth's observed seismic behavior, but none gives a completely satisfactory explanation. This difficulty arises primarily from the observed complexity of the Earth's seismic behavior.

Among the early hypotheses for the Earth's seismic behavior was Reid's (1911) "elastic rebound" concept. Reid summarized the salient features of this concept as follows:

a. The fracture of the rock that causes a tectonic earthquake is the result of elastic strains, greater than the strength that the rock can withstand, produced by the relative motions or displacements of the neighboring portions of the Earth.

b. The relative displacements are not produced suddenly at the time of the fracture, but they attain their maximum amounts gradually during a more-or-less long period of time.

c. The only mass movements that occur at the time of the earthquake are sudden elastic rebounds of the sides of the fracture towards positions of no elastic strain; and these movements extend to distances of only a few km from the fracture.

d. The earthquake vibrations originate in the surface of the fracture; the surface from which they start has at first a very small area, which may quickly become very large, but at a rate not greater than the velocity of the compressional elastic waves in the rock.