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STATISTICS AND EARTH SCIENCES
A CHALLENGE FOR THE 80'S
THE GEOLOGISTS VIEWPOINT

BY

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Statistics and Earth Sciences
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The Geologists Viewpoint

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Introduction

It used to be that university students took up geology because they were attracted to the outdoors. This attraction developed perhaps because of a weekend field trip, or a summer field camp, or, for the lucky ones, a field season with an oil company. Whatever the reason, to be a geologist was to be among rocks. Traditionally, the role of the geologist has been to unravel the Earth's past. It has not been easy. Ask anyone who has taken a close look at a rock. Invariably, there is a multiplicity of explanations of how any rock came into existence. What is recorded in all probability is a multiplicity of past events, the evidence being only partly preserved; the rest has been obliterated. As a consequence, the rock record is largely incomplete. This is what has made the science of geology so interesting. It is also what has made it so difficult. Interpreting the past has more than its share of uncertainty.

However, times have changed in geology. It is a change moreover, I suspect will occupy a considerable amount of attention in the eighties. The fact is that society is demanding more from science, and from geology in particular. Whereas in the past, the geologist could quietly study and contemplate earth's history, the geologist now is expected to contribute to the solution of societal problems, namely, to provide timely information on the character, location, magnitude and timing of events which affect human activity, to assess the environmental impact of human activities, and to appraise the magnitude of our natural resources (McKelvey, 1979). Clearly, the scope of responsibility of the geologist has been enlarged to include broader and more active participation in the public decision-making process. It is not always a comfortable role. It is a role, however, that the geologist must accept if geology is to retain its vitality and place in society. How fully this role can be accommodated depends on the degree to which geology can become more predictive.

The predictive capability of geology has been growing rapidly in the last decade. A related development has been quantification. Previously, geologists based their inferences on observations which could best be classified as verbal or geometric (as with geologic maps) descriptions. In particular, the data could be classified as belonging to either nominal or ordinal types. What has transformed geology into becoming a more quantitative science is the focus of attention on process. The study of the processes which produce rocks, for instance, has increasingly required a more quantitative approach. Similarly, studies of the processes which affect the Earth's surface and thus affect human activity are also rapidly becoming more quantitative. It is this aspect I wish to deal with in terms of statistics and geology and the challenge for the eighties.

Statistics and Geology

Where statistics and geology come together is in the development of models for prediction. Prediction is used here in the broadest sense to include models for interpretation, estimation and explanation (Shreve, 1979). Thus, models can be developed for relating observational data to model parameters, for providing values of system variables or for representing how a system works, in addition to predicting the future, or past history of a system from its present state.

If there is a certainty, it is that most current models for prediction in geology are inadequate. But after all, this is to be expected in view of the nature of the problem and the inherent difficulties in formulating any model in geology. The three main difficulties are the interdependence of system variables, the nonlinearity of geologic processes, and the extreme range of characteristic time scales involved in the processes. A random element is superposed on all these, making the task of model building even more difficult. If this isn't enough, there is another impediment which, though more psychologic than real, confronts a would-be model builder. This is the distinction that invariably rises as to whether a particular predictive model is genetic or descriptive. A genetic model implies a knowledge of how a process operates and therefore how it responds spatially and temporally. A descriptive model lacks this knowledge and substitutes instead system variables whose relationships are derived through correlation. The former is often characterized by the paucity of data whereas the latter often has an excess. In either case, a choice between the two should not be based on intrinsic qualities but rather on the success achieved in prediction.

The role of the geologist in developing a model for prediction is to identify the critical elements involved in the process, define the nature of the interactions between the elements, recognize the characteristic time scales involved, and decide on whatever geological constraints or boundary conditions need to be considered. The role of the statistician is to translate the conceptual model proposed by the geologist into a form suitable for prediction. The dual role of the geologist and the statistician is to evaluate the results of applying a model in known situations and, ultimately, to make predictions in real situations. This is the challenge of the eighties.

To understand what confronts the geologist in developing a model for prediction, let us consider briefly two examples.

Cyclic Landslides

In California extensive landslides and mudflows are common. While there is rarely loss of life associated with these events, there is often considerable loss of structures and incurred economic hardship. In many areas, the landslides and mudflows are thought to be triggered by the spring runoffs following unusually wet winters. It would be desirable therefore to develop a climatic-geomorphic model for predicting the occurrence of such events so that subsequent economic losses could be minimized.

From field observations made in an area of southern California by two U.S. Geological Survey geologists, D.M. Morton and R.H. Campbell (1978), it has been suggested that landslide and mudflow events are parts of a composite cycle of landslide activity. In particular, this activity includes three recognizable stages distinguished from one another by size of the associated deposits, mechanism of displacement, and proximate causes. The stages occur in sequence, the deposits of the first cycle being removed to positions further down-canyon by the activity of the second and third stage landslides. What offers the chance to develop a model for prediction is that the three stages are interdependent, occur in sequence, and are of different duration.

First-stage landslides with recurrence intervals estimated at several thousand years and involving several million tons of material are represented by huge slumped masses from steep bedrock slopes in canyon-heads. What triggers a landslide is largely unknown although it must be expected that severe earthquake shaking which is common in the area would be a significant factor for some of them.

Second stage activity develops as streams cut a network of branching channels into the massive first-stage deposits. The second-stage landslides with recurrence intervals estimated at tens of years and involving on the order of a million tons of material are chiefly slumps from the older slide mass and from adjacent bedrock slopes. Second-stage slides are apparently preceded and triggered by a series of high-precipitation winters. The movement of these slides is downslope toward actively eroding drainages.

Third-stage activity includes mudflows that accompany the spring melting of snowpack. These flows recur annually and move hundreds of thousands of tons of debris down the stream channels to depositional reaches in major fans. The velocity of the mudflows is variable from inception to deposition. Some flows have been timed at just under 2 feet per second over a distance of a mile.

Weather conditions are known for several previous episodes of second- and-third-stage landsliding. Triggering of second-and third-stage landslides is thought to be largely governed by weather as shown by precipitation records for 1925-26 through 1973-74 rainfall years (October through September) for an area in southern California (fig. 1). The two recorded periods of greatest mudflow activity followed the two wettest winters.

Removal of sufficient amounts of the first-stage landslide mass to the fan by second- and third-stage events resets the bedrock slope of the main drainage for another first-stage event. Thus, there is a complete cycling of events which occurs over a period of time, depending on the magnitude and intensity of the triggering forces.

Mudflows clearly pose a recurring threat to parts of southern California. Available data indicate that climatic conditions coupled with the geomorphic state of surface land forms could be used to predict the occurrence of spring mudflows. Using data now available, it should be possible to devise models which could be used to predict spring mudflows a year or more before their occurrence.

To do this, the geologist and the statistician need to combine their talents to devise a model which takes into account the interplay of events in terms of frequency, duration and magnitude of precipitation which leads ultimately to the occurrence of a mudflow. This would be coupled with detailed mapping in heterogeneous ground to establish the relative stability of landslide areas. Such mapping would indicate where potential hazards exist. Thus, the aim is to provide a space-time prediction.

Seismic Gaps

No other natural phenomenon has captured the interest of scientists and laypersons alike or caused as much damage to structures as earthquakes. It hardly needs stating that a recurrence of an earthquake, of the magnitude which shook San Francisco in 1906, in a heavily populated area today would result in a severe loss of property and life. As we all know, an earthquake is the sudden release of stress in the ground. As geologists well know, it is not yet possible to predict the magnitude and time of occurrence of a major earthquake. This doesn't mean that theories for earthquake prediction do not exist. Just five years ago, for instance, geophysicists thought they had finally found a realistic model of how rocks along a fault act just before an earthquake. The model, it was hoped, could be used to predict future quakes (Science News, 1974). The theory simply said that accumulating pressure on subterranean rocks caused cracks to open (dilate) to relieve the stress. Water from surrounding rocks flowed into the newly formed fissures causing a drop in the pore pressure. When the fissures became saturated with fluid, pressure was restored and this triggered an earthquake. This theory of dilatancy as it was called, gave rise to patterns of rise and fall of pressure which, it was thought could be related to the time, size, and location of an ensuing earthquake. Using such precursory phenomena, Chinese scientists successfully predicted a quake in Haicheng in February, 1975. The theory apparently failed, however, to predict a major earthquake in 1976 that reportedly killed more than 650,000 people in Tangshan. As with most of the earlier models for prediction, it was not that the theory was wrong, but rather that it was inadequate.

What has happened since is that geologists and geophysicists as well as looking for precursors to enable them to state stime, place, and magnitude for expected earthquakes - are also concentrating on the more modest goal of identifying those areas of the world that may be most susceptible to major earthquakes (Douglas, 1979).

Recently, a group of researchers from the Lamont-Doherty Geological Observatory of Columbia University (McCann and others, 1978) have put forward a statistical occurrence (recurrence) model for forecasting large magnitude earthquakes along the major tectonic plate boundaries of the world. Since World War II, a massive array of evidence has led to the interpretation that the earth's crust is composed of mobile plates each abutting one another and producing stresses along the boundaries.

The intriguing aspect of this model for forecasting is that major earthquakes are forecast for regions along active plate boundaries which have not experienced a major earthquake for more than 30 years but where a major earthquake occurred more than 100 years ago. Such regions are called seismic gaps. Seismic gaps along the "rim of fire" (active zone of volcanic activity), that is, the plate boundaries surrounding the Pacific Ocean, is shown in figure 2. The zones of greatest seismic potential for major earthquakes are shown in black. One such gap marked by a star along the western coast of Mexico may have been filled by a major earthquake which occurred November 29, 1978. This should not be interpreted to mean that gaps of high seismic potential are areas in which a major earthquake is imminent but rather that such gaps are areas in which a major earthquake is likely to occur within the next few decades.

Since plate tectonic theory indicates that plate boundaries are continuous, a problem arises as to what defines the areal extent of a seismic gap. The basic concept that has been applied based on observations is that rupture zones of large shocks are delineated by aftershock activity and that aftershock zones of nearby large earthquakes tend to abut without overlapping. A particularly good example is to be found for large earthquakes near northern Japan (after Mogi, 1968 and Sykes, 1971) shown in figure 3. Double circles are locations of main shocks; single circles are aftershocks which define the rupture area (solid line). The dashed line marks the zone affected by a series of shocks occurring between 1897-1901. No reliable instrumental data are available for these events. For many areas, however, the rupture areas overlap and are difficult to separate.

The seismic gap theory is essentially a statistical model for prediction. While it may be possible in the future to characterize the seismic potential according to physically more understandable quantities such as the long-term rate of plate motion, or repeat time of large shocks, or the configuration of the interface between two intersecting plates, it is only possible at present, because of the great uncertainty in repeat time, to postulate cutoffs of 30 and 100 years in assigning regions to specific categories of seismic potential.

There are obvious statistical implications for the seismic gap model. The statistician could well take an active role in the further development of this latest attempt in earthquake prediction.

As these two examples demonstrate, the task of predicting future events of natural phenomena is exceedingly difficult. Despite the fact that natural events tend to recur in the same general area over a long period of time, a single event appears to be a unique variation of the overall process. Moreover, these events involve such enormous volumes of heterogeneous materials and such exceedingly large natural forces that small-scale experiments are more or less out of the question. Superposed on an already complex situation are the characteristically long time scales involved. The combination of all these factors makes it extremely unlikely that a single precursor event will be found which provides a master key for prediction. Thus, an unusually wet winter or an unusually quiet seismic zone along a plate boundary cannot be regarded as a necessary and sufficient condition for either a major mudflow or a major earthquake to occur in the short term. More factors have to be considered. Knowledge of the general framework of mudflows or of earthquakes is of great importance therefore in developing predictive models. There are no specific rules to depend on, and most of the general rules have exceptions. Thus, a broad background of experience with mudflows or earthquakes in various geologic settings is essential. The same is true for other large scale phemonena such as volcanic eruptions, tsunamis, landslides, and floods all of which pose varying degrees of societal risk. It is the background of experience which the geologist or geophysicist offers in developing models for prediction.

The present situation suggests that a probabilistic base for current models is lacking. Current models tend toward verbal descriptions based on observations rather than on statements of probability. It is not that quantitative data are lacking; most of the field studies that have been conducted have produced large amounts of data. What has proved difficult is interpreting the observations within a probabilistic framework. It was with great pleasure and interest that I read the recent article by Braham (1979) and the ensuing discussion articles by several statisticians on field experimentation in weather modification in the field of meteorology, a discipline which shares many common features with geology. Needless to say, Braham struck a responsive chord when he so eloquently called for closer cooperation between the meteorologist and the statistician. We need the same cooperation between the geologist and the statistician. I believe, in parallel with the view of Professor Braham, that statisticians should be involved with geologists to the extent of going on field trips, examining rocks, and possibly participating in the data collection in order to gain an appreciation of the variety and complexity of geologic settings. Or better yet, guiding a raft through the rapids, or skiing down a glacier to experience the magnitude of the forces which have so sculptured the landscape.

I hope in these remarks I may have encouraged some of the statisticians in the audience to take a closer look at geology. The reward as well as the challenge in making geology more predictive is a worthwhile pursuit.

References

Anonymous, (1974), "No easy way to quake prediction", Science News, 105, 252.

Braham, R.R., Jr., (1979), "Field experimentation in weather modification", Journal of the American Statistical Association, 74, 57-67.

Douglas, J.H., (1979), "Earthquake research (1): Rethinking prediction", Science News 115, 74-76.

McCann, W.R., Nishenko, S.P., Sykes, L.R., and Krause, J. (1978), "Seismic gaps and plate techtonics: Seismic potential for major plate boundaries", in "Proceedings of Conference VI Methodology for Identifying Seismic Gaps and Soon-to-Break Gaps", United States Geological Survey Open-File report 78-943, 441-584.

McKelvey, V.E., (1979), "The Geological Survey's Centennial: The beginning of a second century of public service", The United States Geological Survey's Centinnial Commemoration, Menlo Park, California.

Mogi, K., (1968), "Some features of recent seismic activity in and near Japan," Bulletin of Earthquake Research Institute, University of Tokyo, 47, 1225-1236.

Morton, D.M., and Campbell, R.H., (1978), "Cyclic landsliding at Wrightwood, southern California - A preliminary report," United States Geological Survey Open-File report 78-1079.

Shreve, R.L., (1979), "Models for prediction in fluvial geomorphology," Journal of the International Association for Mathematical Geology, 11, 165-174.

Sykes, L.R., (1971), "Aftershock zones of great earthquakes, seismicity gaps and earthquake prediction for Alaska and the Aleutians," Journal of Geophysical Research, 76, 8021-8041.

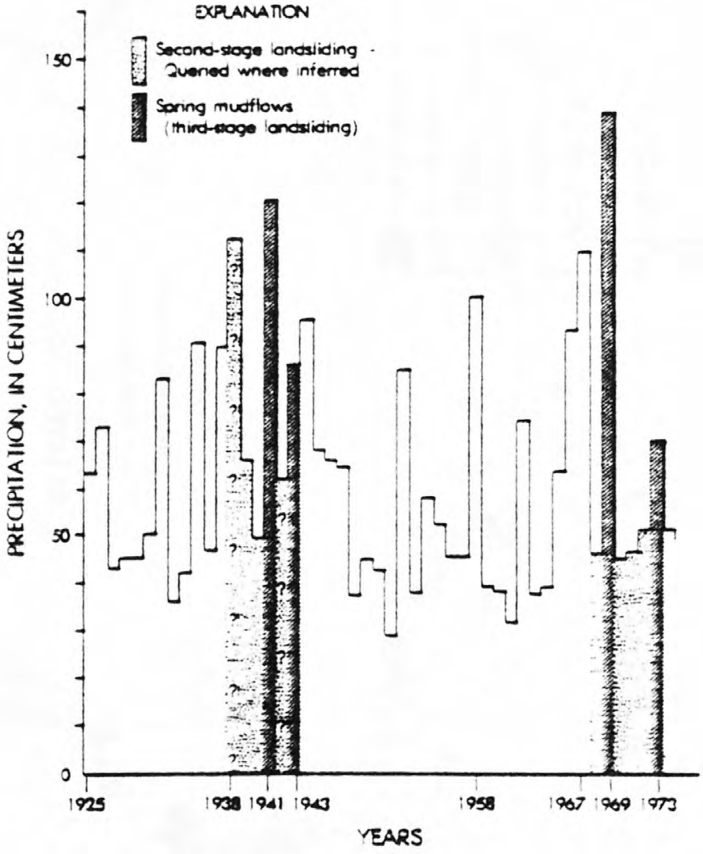

Figure 1. Precipitation records for Big Pines, California area from 1925-26 through 1973-74. From Morton and Campbell (1978).

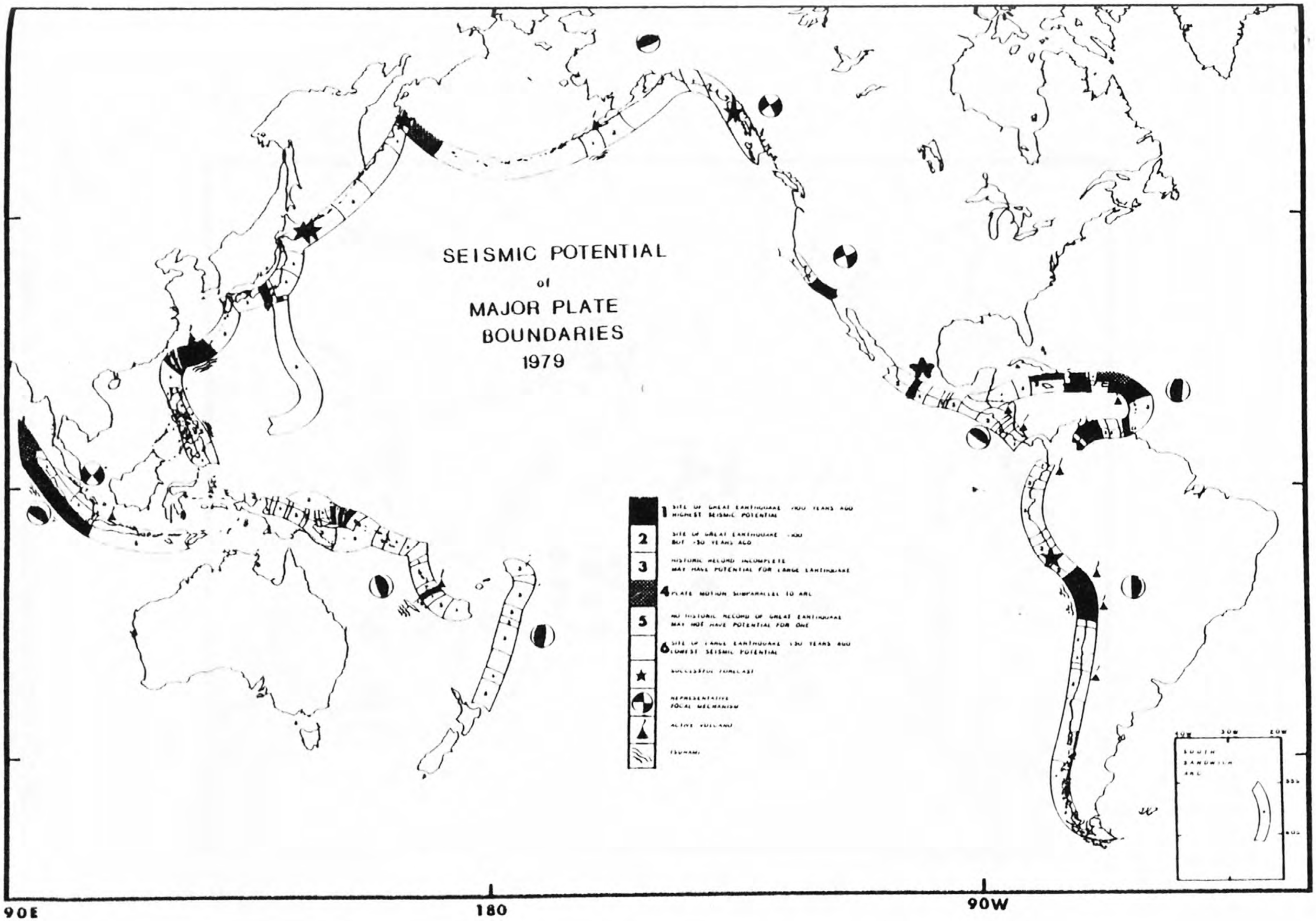

Figure 2. Seismic potential for large magnitude earthquakes for the next few decades along certain major plate boundaries. Dark areas have not ruptured in a great earthquake in over 100 years, and are considered likely candidates for major or great shocks within the next decade or few decades. From McCann and others (1968).

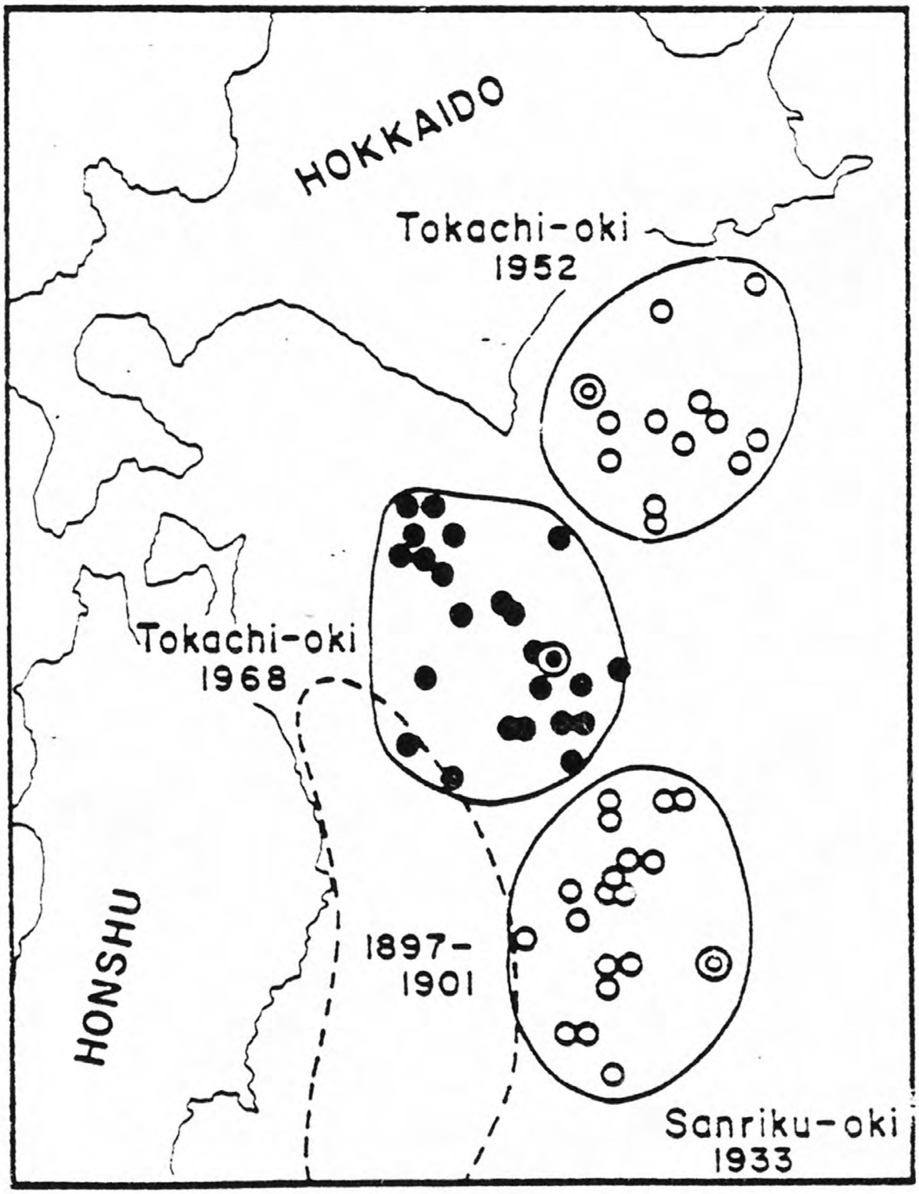

Figure 3. Large earthquakes near northern Japan.
From Mogi (1968) and Sykes (1971)