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Earthquake Prediction and Earthquake Preparedness: The Possibilities to Reduce the Damage from Earthquakes

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EARTHQUAKE PREDICTION AND EARTHQUAKE PREPAREDNESS: THE POSSIBILITIES TO REDUCE THE DAMAGE FROM EARTHQUAKES

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Abstract

The earthquake predictions which are feasible at present though limited both in accuracy and reliability can be used nevertheless to reduce the casualties and economic losses, inflicted by the earthquakes. The key to this reduction is diversity and preparedness of safety measures, combined in flexible scenaria of response to a prediction.

To choose the response one has to know two probabilistic factors: what is the success-to-failure ratio of a prediction method (it has to be known but not necessarily high); and what damage this response may prevent ("estimation of seismic risk reduction").

Safety measures are to be changed in time, since earthquake prediction consists of consecutive, step-by-step, narrowing of the time-space domain, where a strong earthquake has to be expected. The estimation of probability of the destructive earthquakes in an area is changing with time, depending on the current dynamics of earthquake-prone zones, and of our current understanding of it. The safety measures have to be accordingly re-adjusted - escalated or de-escalated, retargeted etc., depending on comparative risk of false alarms and failures to respond.

The possibility of better earthquake prediction in a region like Friuli-Venezia Giulia lies in hierarchical analysis of available data, starting with averaging over large areas. The possibility of better earthquake preparedness lies in diversification and flexibility of safety measures. These possibilities are illustrated by practical examples.

Earthquake prediction: reality and promise

The crust of the Earth is divided into blocks, separated by relatively thin fractured zones, called faults or fault zones.

This system of blocks and, accordingly, of the faults, is hierarchical: large blocks are consecutively divided into smaller ones, down to the grains of rocks.

The blocks move relative to each other. Large part of this movement is realized through earthquakes, in a stick-slip fashion. By and large, the larger are the blocks separated by a fault, the stronger may be the earthquakes on this fault. The strength of the faults is controlled by migration of fluids, petrochemical transitions, microfracturing and other mechanisms, which create strong instability, transforming interacting blocks into a non-linear chaotic system [21].

Stage of prediction. Earthquake prediction can be roughly divided into the following consecutive stages (time-interval, for which prediction is made, is indicated below for each stage):

- **Background,** i.e. mapping of maximal magnitude and maximal strong motion: 100 years.
- **Long-term:** tens of years.
- **Intermediate-term:** years.
- **Short-term:** weeks or days.
- **Immediate:** hours or less.

The territory, where the strong earthquake is to be expected, may converge, up to a limit, from stage to stage.

Only the background stage may claim established methodologies.

Long-term prediction is based mostly on the concepts of seismic gaps [26] and average reoccurrence time [33]; the success-to-failure score of both so far is not encouraging [13, 28].

Intermediate-term prediction, based mainly on premonitory seismicity patterns, has been made algorithmic and is relatively wider tested [11, 20, 22, 23, 37]; the large rate of false alarms is the major drawback of existing algorithms.

Prediction on other stages remains so far occasional, without a systematic score of successes and failures.

Only for one precursor, intermediate-term one (high clustering of earthquakes), a statistical significance is established [29].

All consecutive stages of prediction are accomplished so far in few exceptional cases, such as for the Haicheng catastrophic earthquake in China, 1975.

Intermediate-term prediction is ready for implementation so far on a trial base.

The family of the algorithms developed [25] allows to diagnose the approach of a strong earthquake by analysing transient seismicity in a lower magnitude range*.

The examples of such predictions are shown below in figures 3-6.

Qualitatively the algorithms depict the following premonitory phenomenon: before a strong earthquake the following traits of seismicity in lower magnitude range are increasing:

- intensity of earthquakes' flow;
- its irregularity in space and time;
- clustering of earthquakes;

- range of their interdependence (radius of spacial correlation);
- possibly also the "synergetics" of seismicity, that is, correlation between its different characteristics.

These phenomena may be intepreted as follows:
The response of the fault system to excitation is increasing before a strong earthquake; excitation may be provided by current earthquakes
These phenomena emerge after gross averaging of earthquakes' flow: over years in time, and over the fault systems 5 to 10 times larger than the length of the source of an incipient strong earthquake.

Four paradigms. Worldwide studies and numerical simulation of dynamics of seismicity have led to the following four conclusions, consequentional for R&D in earthquake prediction.

I. *Long range interactions*. The signal, if any, of an incipient strong earthquake may come not from the narrow vicinity of its future hypocenter but from a wide system of faults with different types of dominant motion (strike-slip, dip-slip etc.). Though sometimes regarded as counterintuitive, and certainly complicating the task of prediction, this conclusion is hardly surprising since the occurrence of a single strong earthquake can't be entirely isolated from the dynamics of the whole crust. In particular, an earthquake is generated not by a "single active fault", but by a system of interacting blocks. For example the motion of even a single block leads to different types of faulting on its boundaries.

II. *A set of premonitory phenomena*, even if each of them alone is vaguely expressed and insufficient for prediction, is a promising alternative to a single well-defined precursor. One of the reasons for this may be the fact that we have to look for a prediction method, uniformly applicable in different neotectonic environments; otherwise one can't accumulate a necessary data base.

III. *Many premonitory phenomena (in their robust definition) are similar,* (after normalization - identical) in a wide range of neotectonic environments, from subduction zones to intraplate faults to induced seismicity, and in the magnitude range at least from 4 to 8.5. In the quest for earthquake prediction this allows to analyse jointly the worldwide data. This similarity may seem to be in contradiction with the diversity of seismotectonics. Even in the same locality the most directly relevant fields, i.e. stress and strength, may be different before consecutive earthquakes. However, the similarity does emerge after the averaging. The definition of premonitory phenomena is made robust specifically in order to smooth away the diversity of circumstances.

(*) The software and manuals for application of these algorithms are available in International Center for Theoretical Physics, Trieste (P.O.B. 586, 34100 Trieste, Italy; fax: 39-40-224 575, e-mail: panza@univ.trieste.it) and International Institute of Earthquake Prediction Theory and Mathematical Geophysics, Russian Academy of Sciences, Moscow (Warshavskoye sh.79, k.2, Moscow 113556; fax: 7-095-310 7032; e-mail: mitpan@adonis.ias.msk.su)

IV. An explanation of many regularities in earthquake occurrence lies in the general properties of non-linear dissipative systems, rather than in some process, intrinsic to the Earth's crust as such. Thus the methods of theoretical physics entered the modelling of seismicity [3, 7, 12, 30-34].

Some regularities can be reproduced by the *models of cellular automata type*. The active lithosphere seems to be one of the systems which stay permanently near a critical state; moreover, the large energy discharge does not introduce stability. P. Bac named this behaviour *self organised criticality* [3].

Phase transition was found in some of these models. This became their first direct link to earthquake prediction: a potential precursor discovered in a model first [30].

Other regularities in earthquake occurrence do require less general models, allowing for *geometry of lithospheric blocks and rheology of their interaction* [9].

Models of both types can generate long homogeneous in time series of modelquakes, i.e. rather realistic artificial earthquake catalogues. Using them, the existing prediction algorithms may be tested, and new algorithms developed. This technique allows both to enhance the algorithms and evaluate the quality of modelling.

Predictability of non-linear systems is rather limited. The hope to enhance it lies in averaging, possibly - hierarchical one.

The estimation of the limits of predictability of strong earthquake may be based on the analyses of above-mentioned artificial catalogues.

Another possibility to predict a critical change in a non-linear system arises when this change occurs as a part of a sequence, startling with some non-critical observable phenomena. Then, even if the occurrence of the sequence is unpredictable it may be noticed in advance of the critical change.

How to establish R&D in earthquake prediction for a region? The hope for better prediction lies in the fact, that the vast resources of accumulated data and of emerging theory remain yet untapped. The above discussion suggests the following guidelines:

- To consider not only the region, for which prediction is attempted but the surrounding regions as well. For prediction of earthquakes of magnitude ≥6.5 in Friuli-Venezia Giulia at least adjacent areas of Yugoslavia, Alps, Po Valley and Appennines, up to Ancona have to be included in monitoring.
- To proceed from the whole to details. considering first the strongest averaging in description of relevant processes. For the Friuli-Venezia Giulia region it means to start with the maps of 1:500,000 to 1:2.5 mln scales, and to consider first the spacio-temporal characteristics of the structures of the linear size of the order 10^2 km, for time-intervals 1 to 10 years.

- To explore the similarity of premonitory phenomena in different areas and magnitude ranges. Moreover,
- To monitor, among others, general symptoms of instability, which were observed in other non-linear systems. hypothetically, premonitory phenomena outlined on page 3 deserve attention for other fields too.

Comparison with tradition. These guidelines are in a way opposite to some more traditional approaches, which start with installation of detailed observations, the hunt for precursors etc.

A wealth of information was thus accumulated, but it did not lead to earthquake prediction yet: strong earthquakes keep occurring unpredicted in the very middle of dense state-of-art observational systems of almost futuristic proportions.
This failure is partly due to the *general impossibility to understand a non-linear system by going into more and more details.*
The limited successes in the reproducible prediction were obtained so far by averaging of the relatively routine observations, that is from a small and simplest fraction of the already collected data.

Safety measures: an escalating sequence

Diversity of damage. Earthquakes may hurt population and economy in the exceedingly diverse ways:
- triggering of ecological disasters by release of dangerous materials radioactive, toxic, genetically active etc.;
- partial or total destruction of buildings, lifelines and other constructions;
- damage to the objects inside the buildings;
- fires;
- triggering of other natural disasters, such as floods, avalanches, landslides, tsunamies, liquefaction of the ground etc.

As dangerous are the socio-economic impacts of the earthquakes:
- disruption of vital services
- supply, medical, financial, law enforcement etc.;
- epidemics;
- disruptive anxiety of population, profiteering and crime;
- interruption of normal functioning of economy, e.g. a drop in industrial production and employment as well as destabilization of prices, credit, commerce, stock market etc.

These calamities are developing in different time-scales. ranging from immediate damage in the epicentral zone to long-term chain reaction. lasting years and spreading over large regions.
Some of these calamities may be inflicted by undue release of an earthquake prediction.
The past experience concerns mainly the damage in a locality, i.e. to a construction, ground etc. The integrated damage, affecting socioeconomic infrastructures and ecology in epicentral zone and, eventually, spreading beyond it, has been studied in fewer cases and it is more difficult to foresee: the infrastructures are changing and ecology becomes more fragile, annulling past experience. It is clear, however, that *in spite of technological progress our vulnerability to earthquakes is critically growing* due to:
- population growth;
- overload and destabilization of the ground in densely populated areas;
- proliferation of high risk constructions such as dams, toxic waste disposals, life-lines etc.;
- growing volatility of population;
- growing interdependence of economic activities, both in different regions and different fields.

The diversity of safety measures, which may reduce the damage, can be outlined as follows.

Permanent safety measures maintained during the decades:
- Restriction of land use, especially for high-risk objects and earthquake-inducing activities.
- Building code. demanding reinforcement of constructions.
- Tightening of general safety regulations.
- Enforced public safety services.
- Insurance and special taxation.
- Observations and data-analyses to estimate seismic risk and to monitor earthquake precursors.
- preparation of the response to time-prediction, and of post-disaster activities: planning; establishment of legal background; accumulation of the stand-by resources; simulation alarms; training of population etc.

Temporary safety measures activated in response to time-prediction:
- Enhancement of permanent measures.
- Emergency legislation (up to martial one), to facilitate the rational response to prediction
- Mandatory regulation of economy.
- Neutralization of the sources of high risk: life-lines; nuclear power plants; chemical plants; unsafe buildings etc., up to suspension of operation partial disassembling, demolition ....
- Evacuation of population and highly vulnerable objects (e.g.. schools and hospitals).
- Mobilization of post-disaster emergency services.
- Preparation of measures for long-term post-disaster relief (restoration of dwellings, jobs, production, credit etc.).
- Monitoring of socio-economic changes, and prevention of prediction induced hazards.

These measures are in different forms applicable on international, national, provincial and local levels.

Hierarchy of safety measures. Each measure requires its own lead time to be activated, from seconds to years, and it can be realistically maintained only during a certain time-period from hours to decades.

Similarly different measures can be realistically spread over different territories, from selected points to a country and even wider.

The safety measures listed above are not independent but form an obvious hierarchy: they make more sense, if activated in a certain order. Many measures listed above make sense only in a certain set, as a part of a scenario of response to prediction.

Current seismic risk and practical decision

Complicated and erratic process:

strong earthquakes ===> strong motion of the ground ===> damage to population and economy under certain safety measures

can be summarised for the decision maker as estimation of seismic risk, that is probabilistic distribution of the damage from the earthquakes [14-19]. The damage is estimated for a territory, time-interval and vulnerable objects for which the safety measures are contemplated.

The actual risk (possible damage) is very different for the objects of different type (e.g.. megacity village, desert, gas pipeline) with the same reoccurrence of strong motion. The safety of these objects requires different decision. That is why parallel estimations of seismic hazard for objects of different types are often necessary. and the objects of different geometry has to be considered: for an area (e.g. populated one); a system of lines (e.g. lifelines); a set of points (e.g. small towns) etc.

Seismic risk is directly measured by several components: the number of casualties of different degrees and by economic losses.

Undirect measures of risk, which are easier to estimate, may be also useful: total number of people which may be present in zones of strong motion of different levels; and the total value of property in such zones. in terms of its cost or production capacity etc. Both for population and property the time dependence has to be allowed for.

Most of the practical problems require to estimate seismic risk for a territory as a whole, and within this territory - separately for the objects of different types: populated areas, lifelines, sites of the vulnerable constructions etc. The choice of the territory and of the objects is determined by jurisdiction and responsibility of the decision maker who is using the estimations. The examples of seismic risk estimations are given below, in figs. 9-13.

An image of the territory under consideration has to be created in order to estimate seismic risk. This image consists of the following primary models: of earthquake occurrence; of the strong motion, caused by a single earthquake; of territorial distribution of population and property, along with their dynamics, and a model of damage, caused by an episode of strong motion. These models, except may be the third one, are intrinsically probabilistic. Examples of their estimations can be found in [4, 5, 16, 18, 19, 27].

Among the most common representations of seismic risk are also the maps showing territorial distribution of its indirect measures, attributed to the points on the map: average reoccurrence time for strong motion of a given intensity and/or maximal intensity of strong motion during a given time-interval.

These maps may be useful for preliminary orientation, but hardly suitable for decision making for the following reasons.

Due to the high irregularity of all the processes involved, the average measures of seismic risk may be misleading, even when dispersion in supplemented; this may be illustrated by comparison of average and confidence limits of seismic risk [4, 5, 16, 21]. That is why the whole distribution function for these values is also considered in a single point. However even such function has a limited meaning: the episode of a strong motion in a specific point is such a rare event that it can only be ignored, at the best - given low priority ("put on the back burner") by a decision-maker, responsible for this point only.

That is why most of the decision concerning seismic risk refer. implicitly or explicitly, *not to separate points, but to a territory as a whole, where the safety measures have to be undertaken.*

Tempting as it is. seismic risk for a territory cannot be estimated by integrating over the maps showing the risk for each point. This is impossible, as seismic risk in different points is interdependent: the points, close to each other, may be affected by the same seismic source. This interdependence is of paramount practical importance causing the increase of dispersion of seismic risk. Integration over the map may provide only the average values which are as a rule misleading.

For similar reasons the population and property affected cannot be obtained from the size of the objects affected, multiplying it by density of population cost of construction etc. That would give wrong results for two reasons: first, because of inter-dependence of risk in neighboring points; second, because we have to allow for the timedependence of density of population cost of construction etc.
Similarly, one cannot evaluate seismic risk by "multiplying seismic hazard by damage".
So, to evaluate each measure of seismic risk, we have to step back to the primary models.

Useful methodologies

We shall illustrate here some results which can be obtained on the basis of the already existing or slightly supplemented data base.

Image of the region. - *Hierarchical mapping of earthquake-prone lineaments and recognition of areas where strongest earthquakes may occur* [2. 6. 10]. The lineaments can be outlined by joint analysis of the comprehensive set of maps - tectonic, geophysical and geomorphological ones, along with satellite photos of the Earth's surface. The method of analysis is called "morphostructural zonation" [2, 10]. Its major feature is the following. The territory is divided first, approximately into the areas, different in structure, morphology and tectonic history. Only then, near the approximate borders of the areas. the evidences for the lineaments are looked for.
The example is shown in fig. 1. The faults outlined by tectonic evidences only are shown for comparison on the left side of fig. 1.

- *Parameters of seismicity*. Figs. 2. 3 show confidence limits for the Gutenburg-Richter law. The method used [4. 5. 16. 27] allows to analyse jointly the data for different time-periods, taking into account difference in the accuracy and completeness of the data.

Intermediate-term earthquake prediction

Figs. 4-6 show prediction for different regions of Italy [8, 23, 24] and for California [23]. Territorial uncertainty of prediction can be reduced by factor 5-10 in second approximation, provided "Mendocino scenario" [22]. Fig. 7 illustrates the power of averaging: it reveals premonitory activation in probably chaotic earthquakes' sequence. It may be insufficient alone, but useful in a set of premonitory patterns.
Fig. 8 shows a numerical model, simulating seismicity in a model which reflects general regularities in the systems of interacting elements [35]. Other models which may reproduce the real geometry of the faults' system are described in [91.

Statistical significance of a prediction algorithm can be evaluated by the method. described in [29]. *Probabilistic presentation* of prediction with the trade off between false alarms and failure-to-predict is essential for optimization of safety measures [28].

Seismic risk

Figs. 10-14 show its different estimations made for qualitative orientation of civil protection system (figs. 10-12); for purposes of insurance (Table 1), and for correction of a railroad building code (figs. 3. 14).

REFERENCES

1. Aki K., 1981. A probabilistic synthesis of precursory phenomena. Maurice Ewing Ser., 4, pp.566-574.

2. Alexeevskaya M., Gabrielov A., Gelfand I., Gvishiani A, and Ranzman E., 1977. Formal morphostructural zoning of mountain territories. J.Geophys.Res., 43, p. 227-233.

3. Per Bak, Chao Tang and Kurt Wiesenfeld, 1988. Self-organised criticality. Physical Review A, vol. 38, No.1, pp.364-374.

4. Caputo M., Keilis-Borok V.I., Kronrod T.L., Molchan G.M., Panza C.F., Piva A., Podgaetskaja V.M., Postpischl D., 1973. Models of earthquake occurence and isoseismals in Italy. Annali di Geofisica, XXVI (2-3), pp.421-444.

5. Caputo M., Keilis-Borok V.I., Kronrod T.L., Molchan G.M., Panza C.F., Piva A., Podgaetskaja V.M., Postpischl D., 1974. The estimation of seismic risk for central Italy. Annali di Geofisica, XXVII. pp. 349-365.

6. Caputo M., Keilis-Borok V., Oficerova E., Ranzman E., Rotwain I. and Solovieff A., 1980. Pattern recognition of earthquake-prone areas in Italy. Physics of the Earth and Planetary Interiors, 21 (1980), pp.305-320.

7. Carlson J.M. and Langer J.S., 1989, Mechanical model of an earthquake fault. Physical Review A, vol.40, No.11, pp.6470-6484.

8. Costa G., Panza G., Rotwain I. and Staniskova V., 1993. Prediction of strong earthquakes in Northern Italy (in press).

9. Gabrielov A.M., Levshina T.A. and Rotwain I. M., 1990. Block model of earthquake sequence. Physics of the Earth and Planetary Interiors, 61, NN.1-2, pp.18-28.

10. Gelfand I.M., Guberman Sh.A., Keilis-Borok V.I., Knopoff L., Press F., Ranzman E.Ya., Rotwain. I.M. and Sadovsky, A.M., 1976. Pattern recognition applied to earthquake epicenters in California. Physics of the Earth and Planetary Interiors, 11. pp.227-283.

11. Healy J.H., 1990. Report to NEPEC on evaluation of prediction of the Loma Prieta 1989 earthquake made by the algorithm M8 (January 11, 1990).

12. Kadanoff L.P., Nagel S.R., Lei Wu and Su-Min Zhou, 1989. S and Universality in Avalanches. Physical Review A, vol.39, No.12, pp.6524-6573.

13. Kagan, Y. and Jackson, D., 1991. Seismic gap hypothesis: ten years after. J.Geophys.Res., 96, pp.21, 419-421, 431.

14. Kantorovich L.V., Keilis-Borok V.I. and Molchan G.M., 1974. Seismic risk and principles of seismic zoning. Series: Seismic design decision analysis. Department of Civil Engineering, MIT, Internal Study Report No.43, May 1974, 26p.

15. Kantorovich L.V. and Keilis-Borok V.I., 1991. Earthquake prediction and decision-making: social, economic, legislative and civil defence domains. Preprints of International Conference "Earthquake Prediction: State-of-the-Art" Strasbourg, France, 15-18 October, pp.586-593.

16. Keilis-Borok V.I., Vilkovich E.V., Molchan G.M.. 1970. Seismicity and principal seismic effects. Geophys. J.R. Astr. Soc., Vol.21. pp.323-335.

17. Keilis-Borok V.I., Kronrod T.L., Molchan. G.M., 1974. Algorithm for estimating seismic risk. Series: Seismic design decision analysis. Department of Civil Engineering, MIT. Internal Study Report No.43, May 1974.

18. Keilis-Borok V.I., Kronrod T.L. and Molchan G.M., 1984. Seismic risk for the largest cities of the world; intensity VIII or more. The Geneva Papers on Risk and Insurance, 9, No.32, pp.255-270.

19. Keilis-Borok V.I., Molchan G.M., Koridze A.Ch., Kronrod T.L. and Gotsadze O.D,. 1984. An insurance-oriented pilot estimation of seismic risk for rural dwellings in Georgia. Geneva Association, Etudes et Dossiers No.77, pp.85-109.

20. Keilis-Borok V.I., Knopoff L., Rotwain I.M. and Allen C.R., 1988. Intermediate-term prediction of occurence times of strong earthquakes. Nature, Vol.335, No.6192. pp.690-694.

21. Keilis-Borok V.I., 1990. The lithosphere of the Earth as a nonlinear system with implications for earthquake prediction. Review of Geophysics, 28. No.1. pp.19-34.

22. Keilis-Borok V.I., Kossobokov V.G. and Smith S.W., 1990. Reduction of territorial uncertainty of earthquake forecasting. Physics of the Earth and Planetary Interlors, 61. N.1-2, 4p.

23. Keilis-Borok V.I., Kossobokov V.G., 1990. Premonitory activation of earthquake flow: algorithm M8. Physics of the Earth and Planetary Interiors, 61. NN.1-2. pp.73-83.

24. Keilis-Borok V.I., and Rotwain I.M., 1990. Diagnosis of time of increased probability of strong earthquakes in different regions of the world. Physics of the Earth and Planetary Interiors, 61. NN.1-2. pp.57-72.

25. Keilis-Borok V.I., (Editor). 1990. Intermediate-term earthquake prediction: models. algorithms, worldwide tests. Physics of the Earth and Planetary Interiors, 61, NN.1-2 (special issue).

26. McCann W.R., Nishenko S.P., Sykes L.R. and Krause J., 1979. Seismic gaps and plate tectonics: seismic potential for major boundaries. Pure Appl.Geophys., 117, 1082-1147.

27. Molchan G.M., Podgaetskaya V.M.. 1974. Parameters of global seismicity. Series: Seismic design decision analysis, Department of Civil Engineering, MIT, Internal Study Report No.43. May 1974.

28. Molchan G.M.. 1990. Strategies in strong earthquake prediction. Physics of the Earth and Planetary Interiors, 61, NN.1-2, pp.84-98.

29. Molchan G.M., Dmitrieva O.E., Rotwain I.M. and Dewey J., 1990, Statistical analysis of the results of earthquake prediction, based on bursts of aftershocks.Physics of the Earth and Planetary Interiors, 61, NN.1-2. pp.128-139.

30. Narkunskaya G.S. and Shnirman M.G., 1990. Hierarchical model of defect development and seismicity. Physics of the Earth and Planetary Interiors, 61. NN.1-2, pp. 29-35.

31. Newman W. I. and Gabrielov A.M.. 1989. Failure of hierarchical distributions of fiber bundles, I (in press).

32. Newman W.I. and Knopoff L., 1990. Scale invariance in brittle fracture and the dynamics of crack fusion. International Journal of Fracture, 43. pp. 19-24.

33. Nishenko S. and Buland R., 1987. A generic recurrence interval distribution for earthquake forecasting. Bull. Seismol. Soc. Am. 77 (4), pp. 1382-1399.

34. Ogata, Y., 1988. Statistical models for earthquake occurrences and residual analysis for point processes. Journal of the Amer. Stat. Ass., March 1988, Vol.83, No.401. Applications.

35. Pisarenko V.F., Primakov I.M.. Shnirman M. G. Deformation of an array of interacting movable elements. PEPI, 61 (1990), pp.8-17.

36. Vorobieva I. A. and Levshina T. A., 1993. Prediction of the second strong earthquake in a couple (in press).

37. Wyss M. and Habermann R.E., 1988. Precursory seismic quiescence: past present, future. PAGEOPH. Vol.126, NN. 204, pp.279-318.

Figure captions

Fig. 1. Active faults, determined by joint analysis of a wide set of data (right). Faults, determined mainly by tectonic data only, are shown on the left. After [10].

Fig. 2. 95% confidence areas for parameters (A,B) of the Gutenberg-Richter law: LgN(M) = A + (M - 5) B.
1 - Anatolia;
2 - Dinarides and Mediterranean arcs;
3 - Aegean basin;
4 - Alps;
5 - Ibero-Magrib region
After [18].

Fig.3. 95% confidence areas for parameters (A, B) of the Gutenberg-Richter law: LgN(M) = A + (M - 5) B for Italy.
Upper figure corresponds to instrumental data only, lower - to historical and instrumental data together.
1 - zone of intersection of major faults in Central Italy;
2 - zone of linear major faults in Central Italy;
3 - South area, Basilicata, Calabria and Sicilia;
4 - Po-Valley and its mountain frame;
5 - maximum likelihood estimations for each area.
After [4].

Fig.4. Intermediate-term prediction of Irpinia earthquakes. 1980, by algorithm M8. Retrospective analysis. After [23].

Fig.5. Intermediate-term Prediction of earthquakes with magnitudes ≥ 5 in Northern Italy by algorithms CN. After [8].

Top: Alarms and strong earthquakes.
Solid bars - confirmed alarm
Striped bar - false alarm
Vertical line - strong earhquakes: M = 6.5 in 1976 and M=5.4 in 1988.

Bottom: Epicenters of the main shocks, which contributed to the diagnosis of alarms.

Fig. 6. Prediction of a second strong earthquake in Italy by analysis of aftershocks of the first one. Cumulative energy and number of aftershocks are counted for the first 10 or 40 days.
A - first earthquake in a couple;
B - single earthquake.
After [35].

Fig. 7. Earthquake sequence. Power of averaging: premonitory activation before Loma Prieta earthquake in California. 1989. After [23].

Fig.8. Frequency-magnitude plot for the artificial catalog produced by the model of movable frictional elastic disks and map of stress field in the model. Displacement of the elements is forced by constant velocity movement of the frictional horizontal borders in the opposite directions.

Fig. 9. Seismic hazard for eight provinces of Central Italy. F(x) is the probability that x or more km^2 of the territory will fall into the zone of the strong motion of intensity I≥VII during T years.

Solid line: T=30 years; dashed line: T=10 year.
After [5].

Flg.10 Seismic hazard for population of the capitals of eight provinces of Central Italy. F(x) is the probability that x or more people will fall into the zone of the strong motion of intensity I≥IX during a period of 30 years. The annual increase of population is taken for 1%.
After [5].

Fig. 11 Seismic hazard for the economy of eight provinces of Central Italy. F(x) is the probability of the yearly industrial output [mlrd.lire] of the territories, which will fall into the zone of intensity I≥VIII during a period of 30 years (solid line) and 10 years (dotted line).
After [10].

Fig. 12. Seismic hazard for the highway Rome-Naples.
F(X) is the probability that x or more km of the highway will fall into the zone of strong motion of intensity I>VIII (dotted line) and I>IX (open circle line) during a period of 30 years.
After [11].

Fig. 13. Damage prevented by enforcement of the railroad track on the Balkan-Amur railroad (dotted line). Estimation from above (maximizing seismic risk) is considered. Nevertheless, investments will not be compensated by prevented damage, which is purely economical.
After [16].

Fig. 14. 99.5% confidence areas for parameters (A,B) of the Gutenberg-Richter law: $LgN(M) = A + (M - 5) B$ for Baikal. Circle indicates combination of (A,B), which maximized seismic risk.
After [16].

Table 1. Insurance Premium for rural dwellings in Georgia.
Cost of all dwellings $S = 7\ 908.6$ mln roub. Average annual number of destructive earthquakes λ -1.9. Annual growth of the number of dwellings - 1%.
Basic interest rate - 8%.
Cost of insurance - U_T.
m - average damage per event,
σ - its dispersion. After [19].

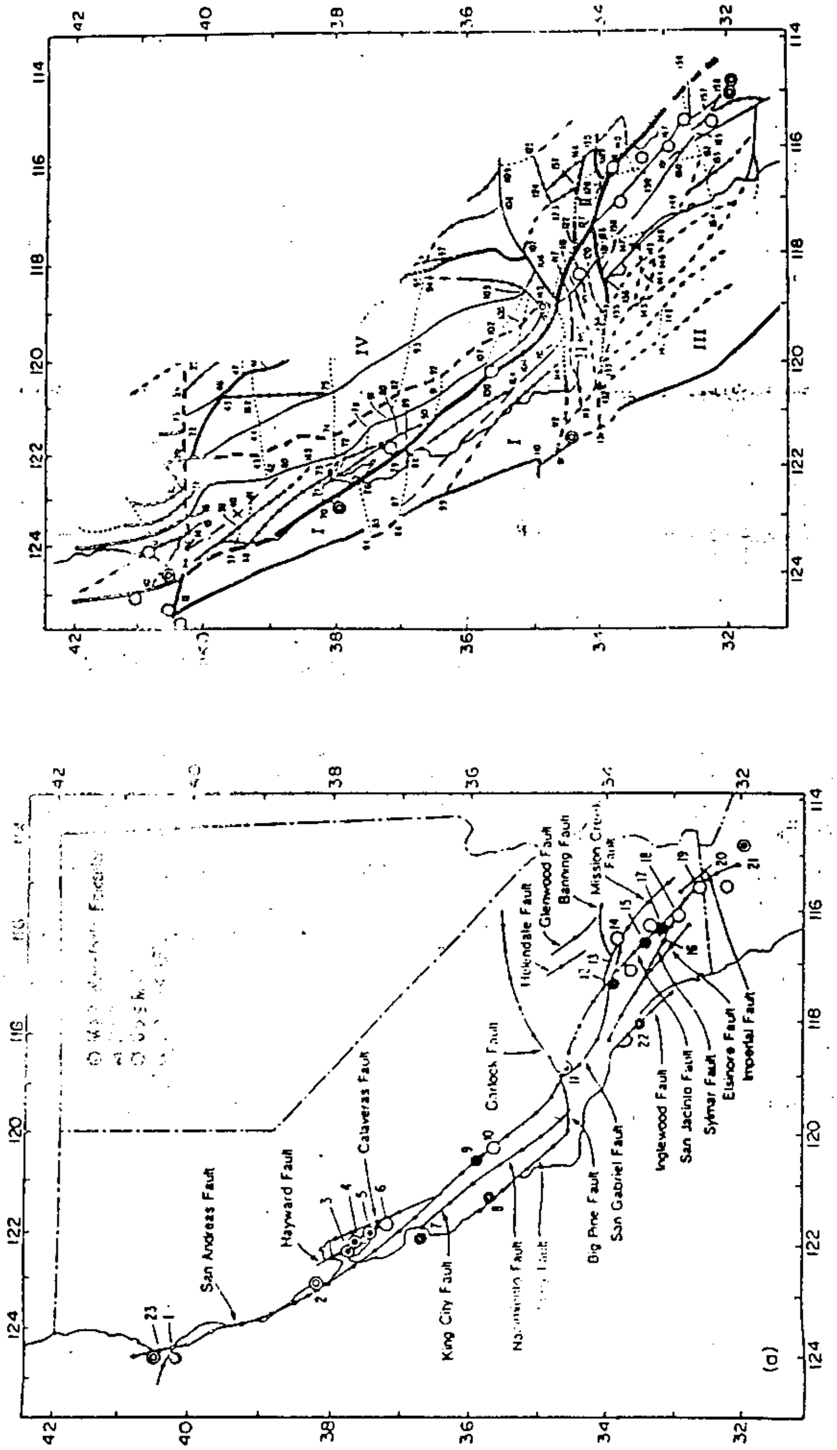
San Andreas Fault
Hayward Fault
Calaveras Fault
King City Fault
Garlock Fault
Big Pine Fault
San Gabriel Fault
Banning Fault
Mission Creek Fault
Inglewood Fault
San Jacinto Fault
Sylmar Fault
Elsinore Fault
Imperial Fault
(a)
I
II
III
IV
42
40
38
36
34
32
114
116
118
120
122
124

Figure 1

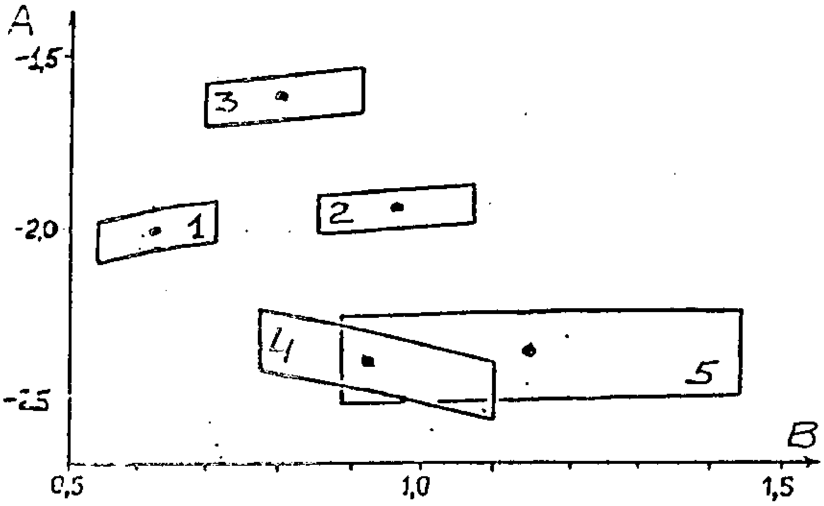

Figure 2

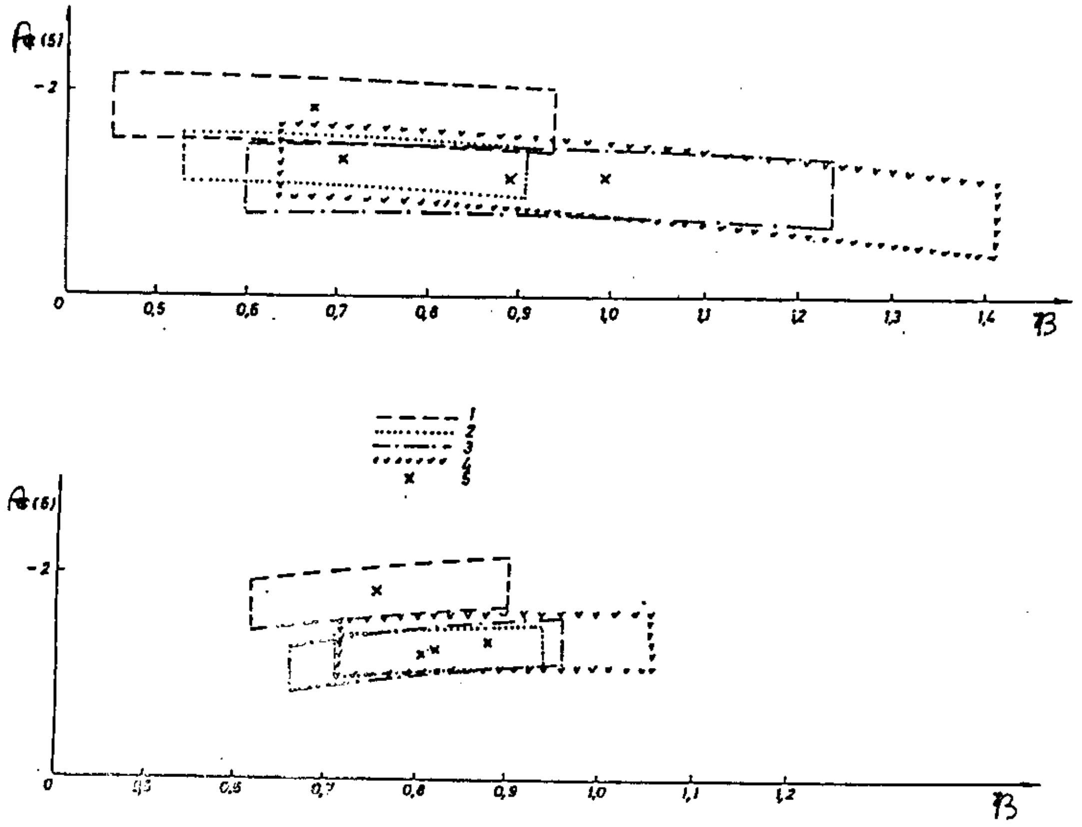
A (5)
-2
0
0,5
0,6
0,7
0,8
0,9
1,0
1,1
1,2
1,3
1,4
B
1
2
3
4
5
A (6)
-2
0
0,5
0,6
0,7
0,8
0,9
1,0
1,1
1,2
B

Figure 3

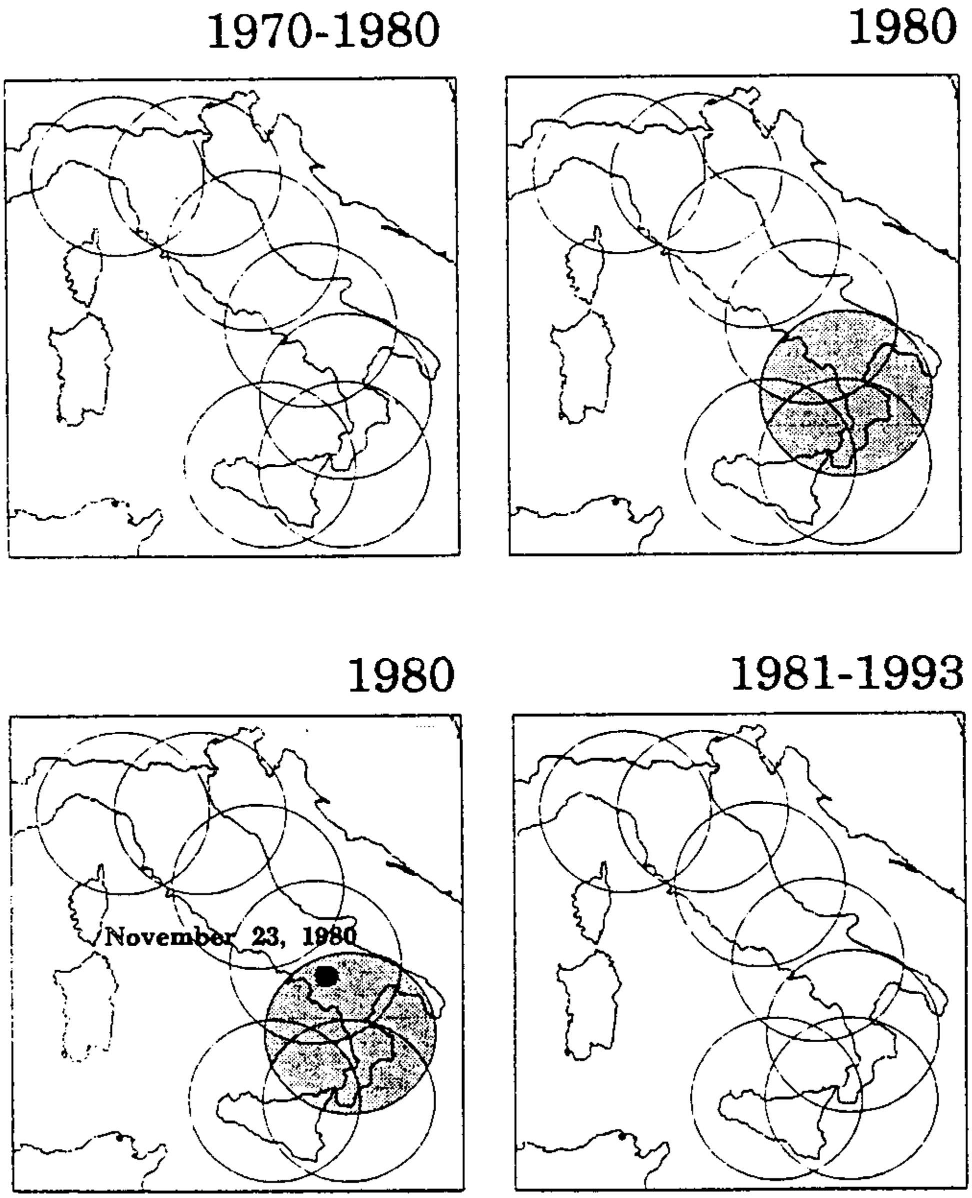

Figure 4

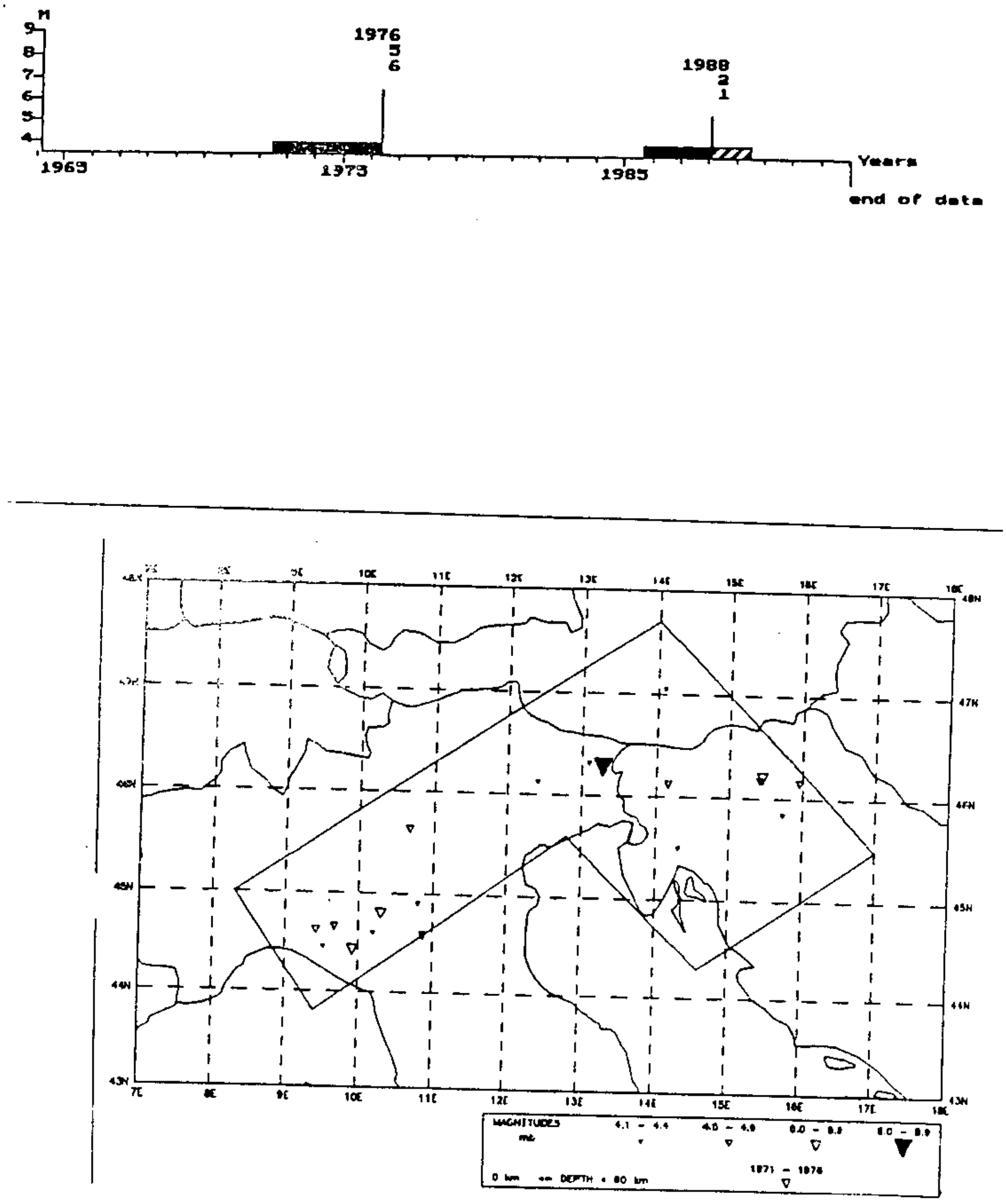
M
9
8
7
6
5
4
1976
5
6
1988
2
1
1963
1973
1985
Years
end of data
7E
8E
9E
10E
11E
12E
13E
14E
15E
16E
17E
18E
43N
44N
45N
46N
47N
48N
MAGNITUDES
mb
4.1 - 4.4
4.5 - 4.9
5.0 - 5.9
6.0 - 6.9
1971 - 1976
0 km <= DEPTH < 80 km

Figure 5

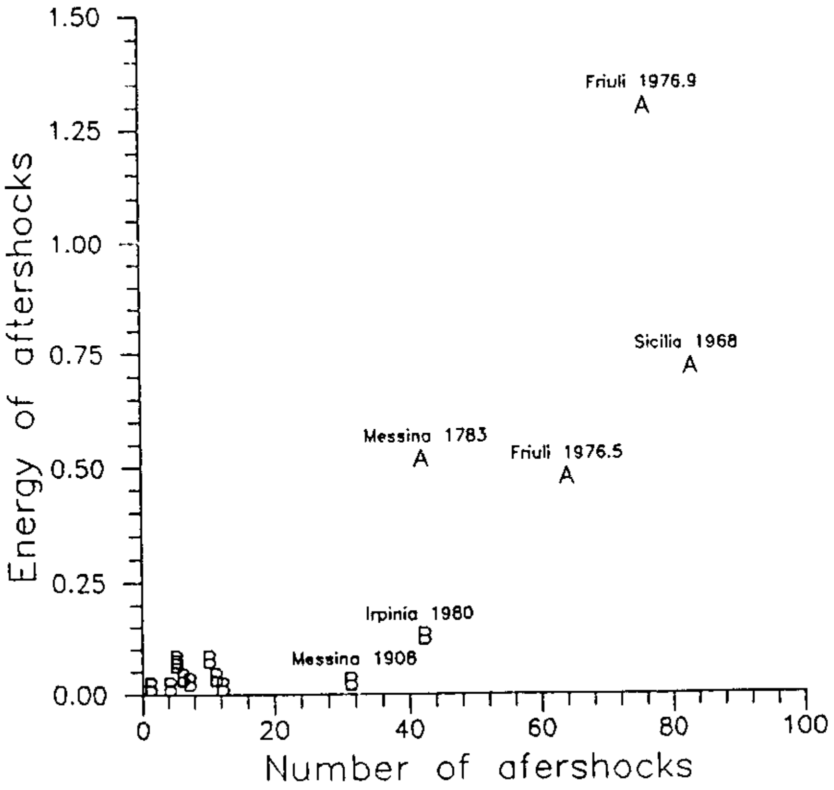
Energy of aftershocks
1.50
1.25
1.00
0.75
0.50
0.25
0.00
Friuli 1976.9
A
Sicilia 1968
A
Messina 1783
A
Friuli 1976.5
A
Irpinia 1980
B
Messina 1908
B
0
20
40
60
80
100
Number of afershocks

Figure 6

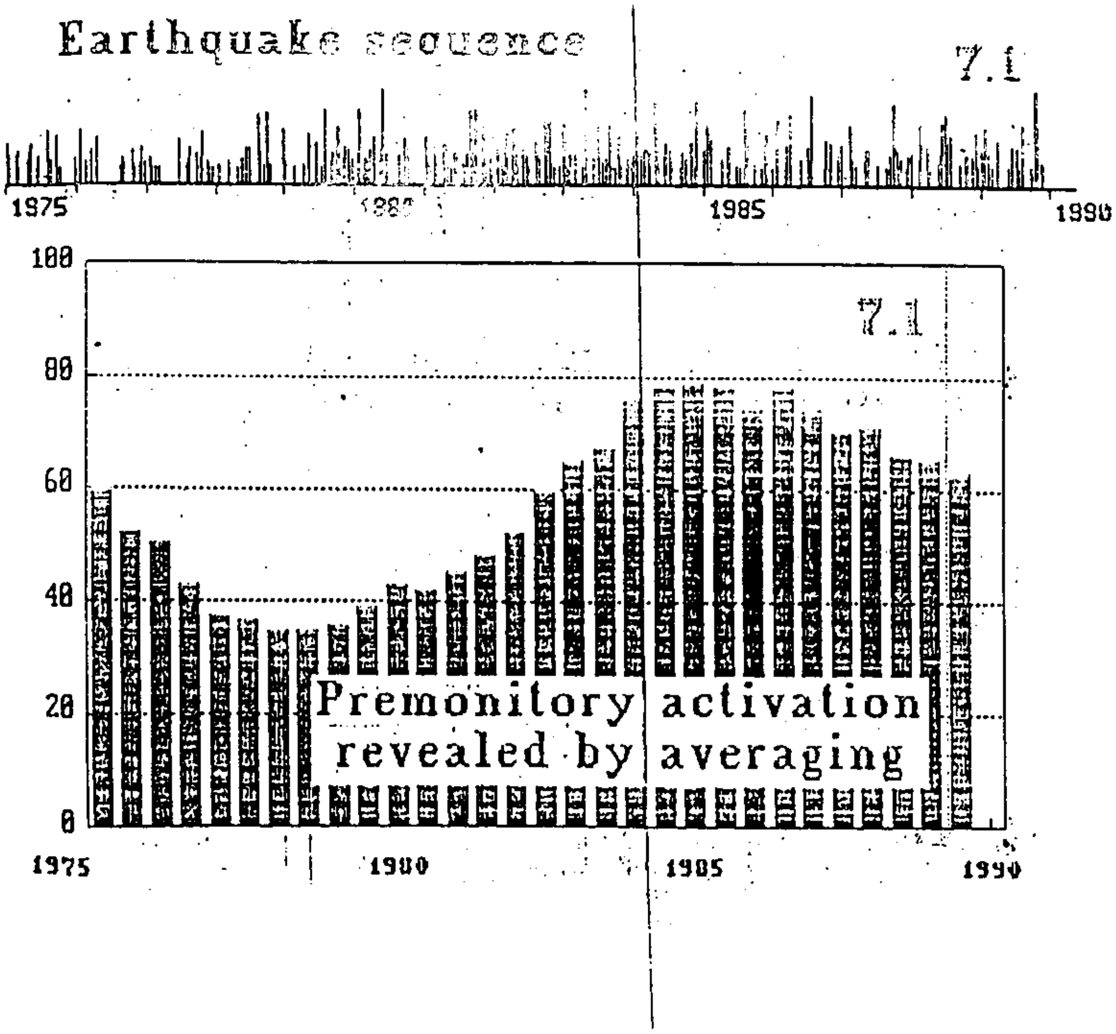
Earthquake sequence
7.1
1975
1980
1985
1990
100
80
60
40
20
0
7.1
Premonitory activation
revealed by averaging
1975
1980
1985
1990

Figure 7

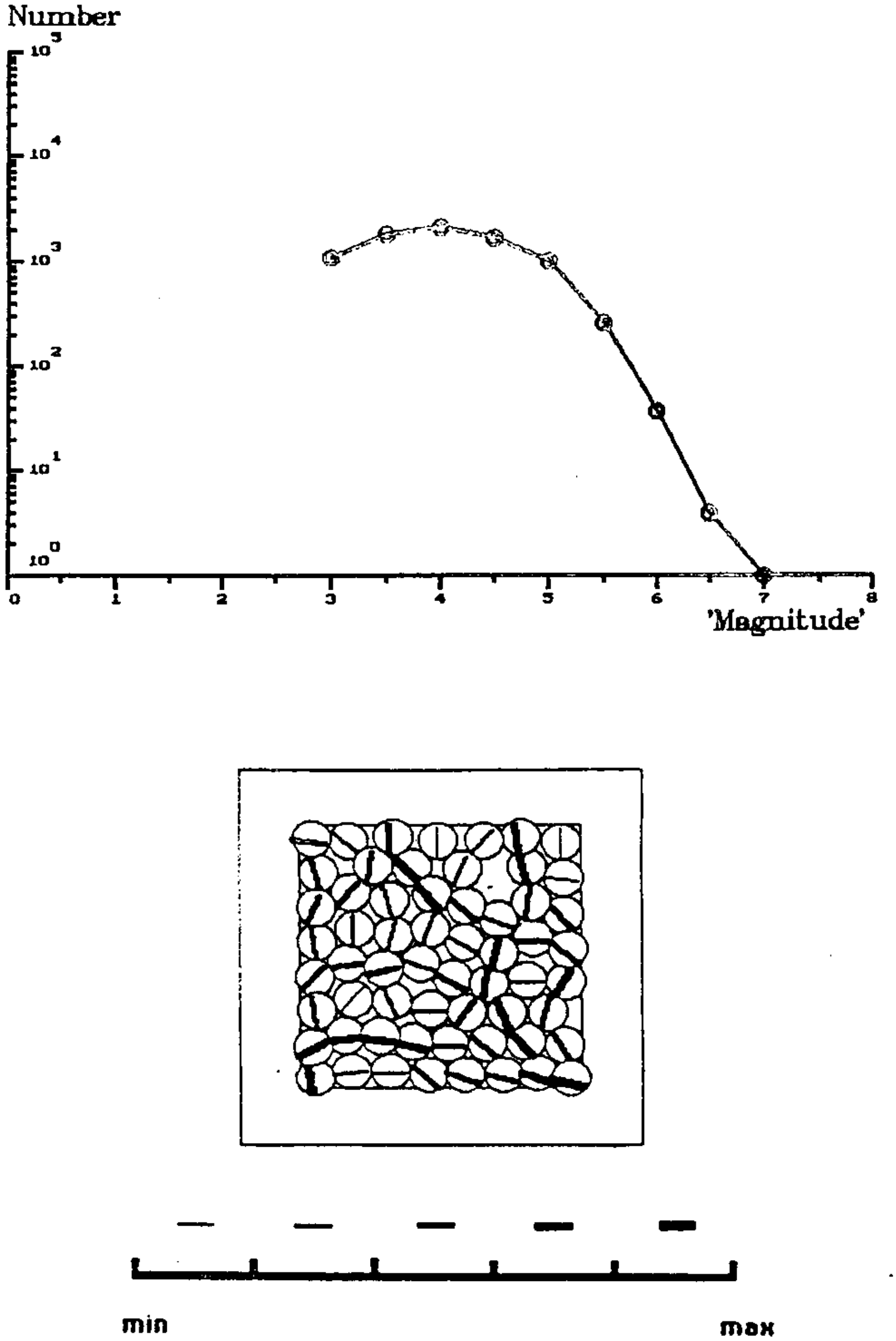

Figure 8

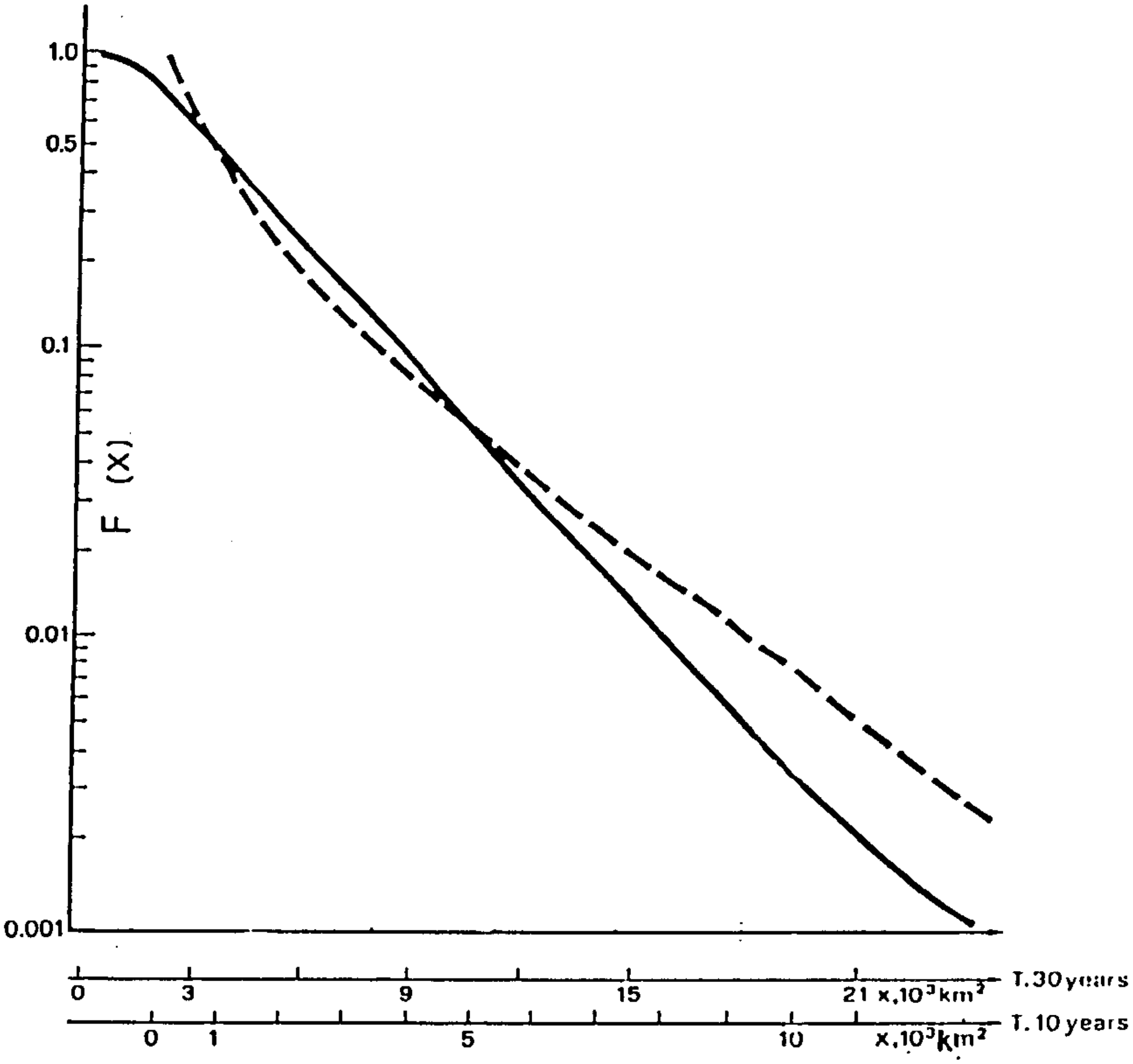
1.0
0.5
0.1
0.01
0.001
F (X)
0
3
9
15
21 x,10³km²
T.30years
0
1
5
10
x,10³km²
T.10years

Figure 9

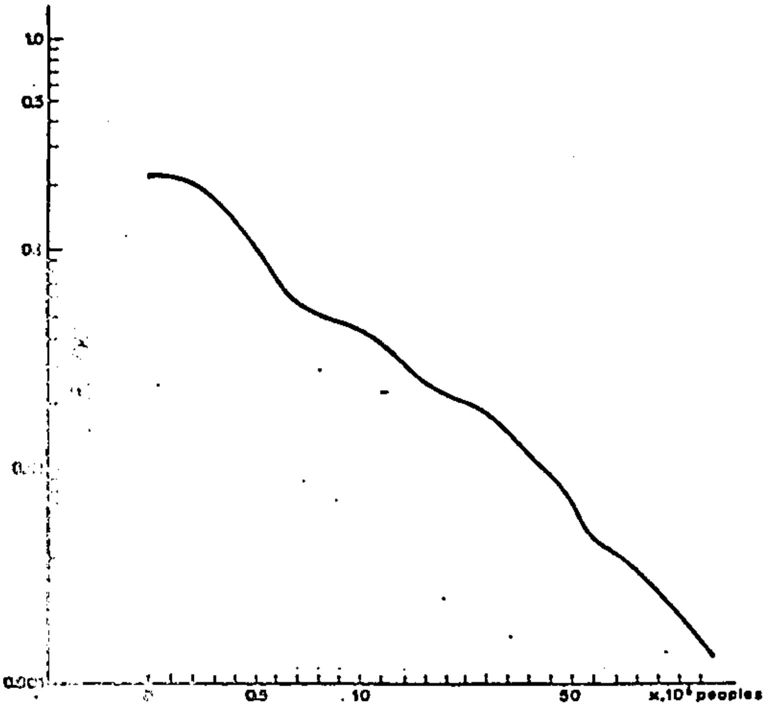

Figure 10

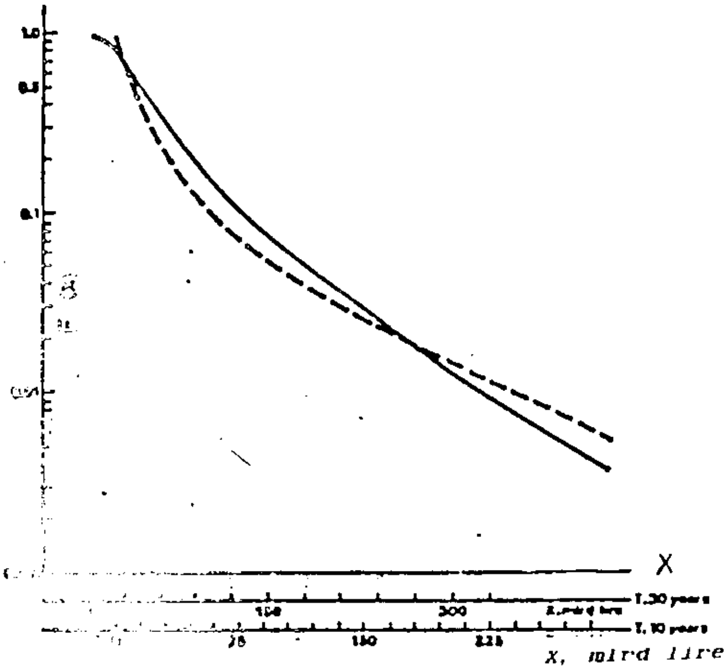

Figure 11

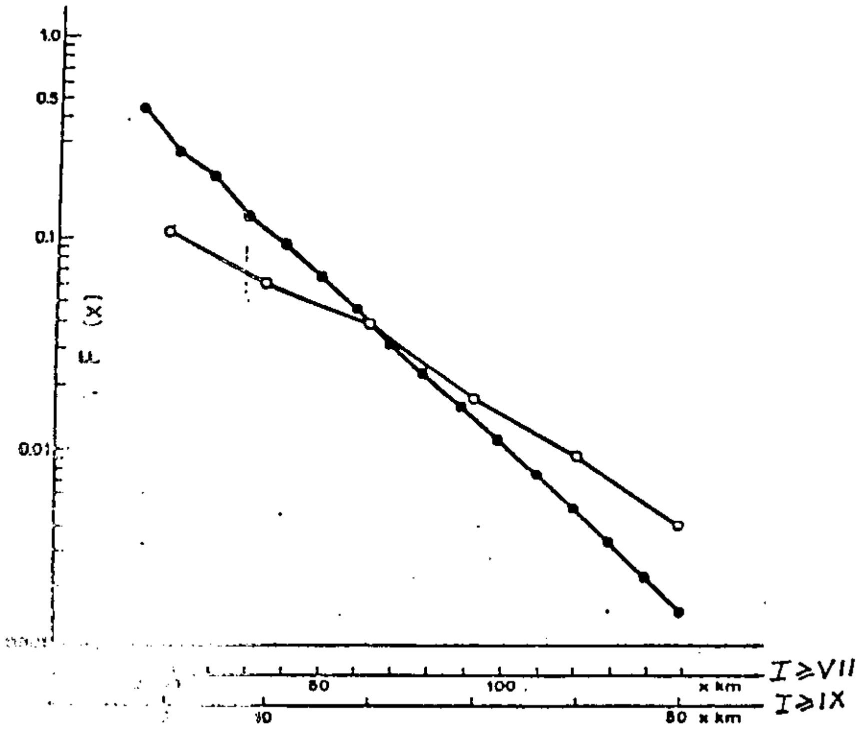

Figure 12

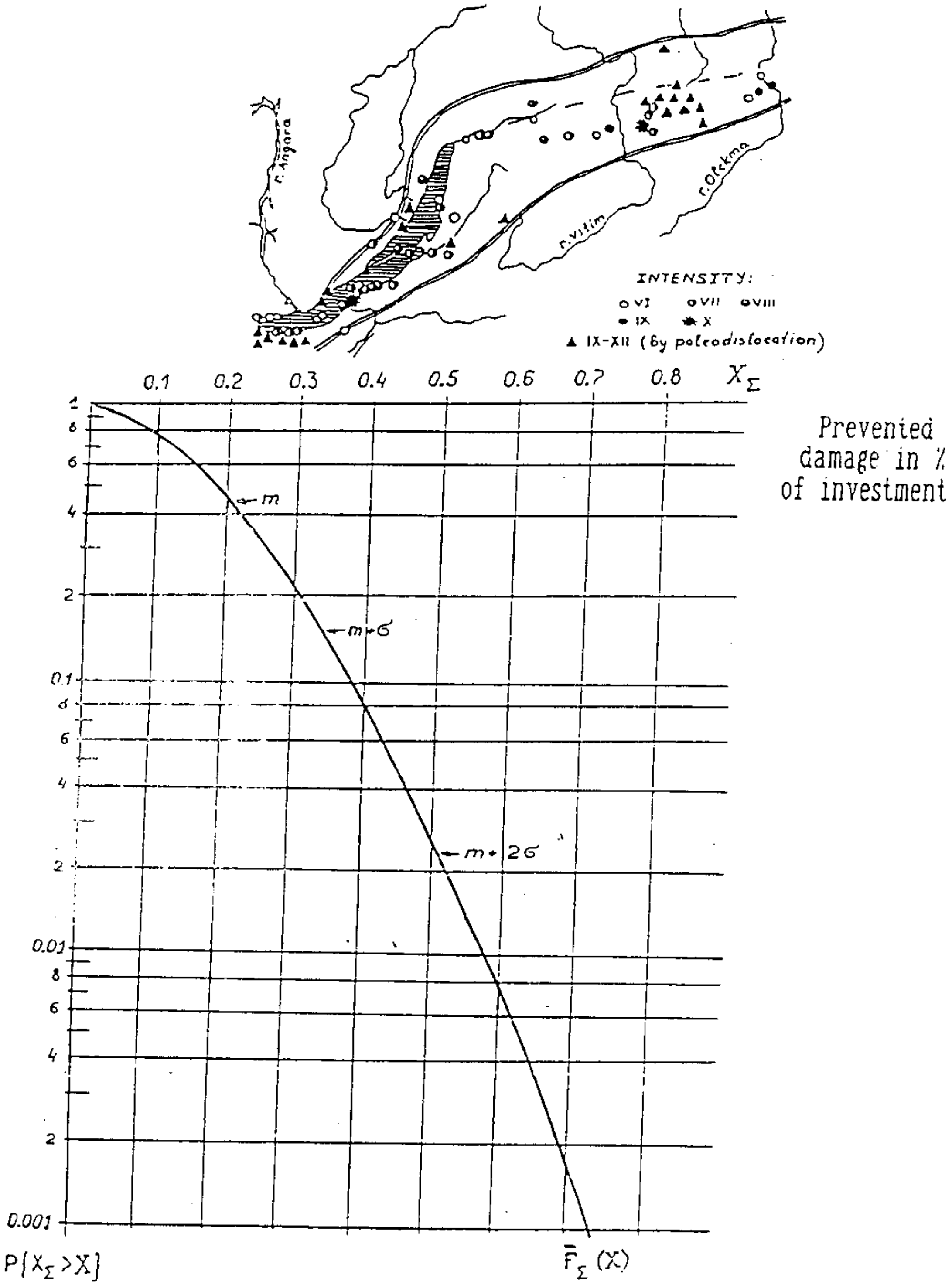
r. Angara
r. Vitim
r. Olekma
INTENSITY:
○ VI
VII
VIII
● IX
X
▲ IX-XII (by paleodislocation)
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
X_Σ
Prevented damage in % of investment
1
8
6
4
2
0.1
8
6
4
2
0.01
8
6
4
2
0.001
m
m+σ
m+2σ
$P\{X_\Sigma > X\}$
$\bar{F}_\Sigma(X)$

Figure 13

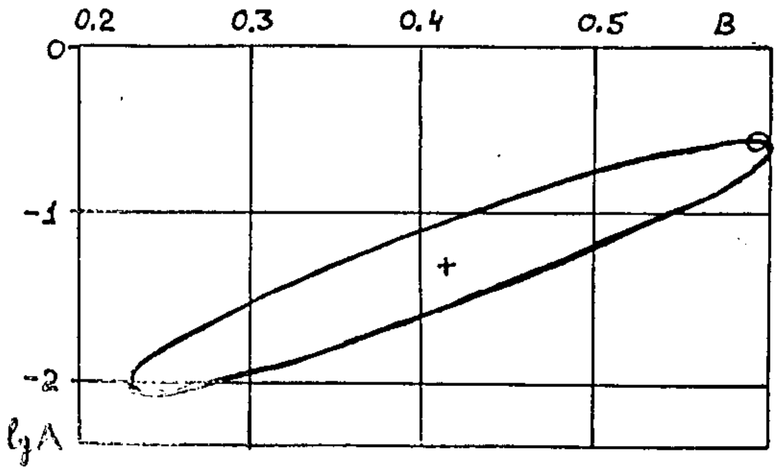

Figure 14

	Risk, $P\{X_T > U_T\}$	T = 5 y.	T = 30 y.	T = 50 y.
Total damage, X_T, % of S		0.98±0.89	2.91±1.24	3.32±1.25
Profit margin:			Rates:	
break even, $U_T = \lambda \cdot m$	> 50 %		0.23 %	
$U_T = m + 2\sigma$	6 %	0.65 %	0.43 %	0.41 %
$U_T = m + 3\sigma$	2 %	0.86 %	0.53 %	0.50 %

Table 1