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EARTHQUAKE PREDICTION BY HYDROGEOCHEMICAL METHODS **

ABSTRACT. — In the last few years the possibility of predicting earthquakes, this old and elusive goal of seismologist and astrologers alike, has became a scientific certitude. It has been clearly demonstrated that many premonitory events precede earthquakes, but our knowledge is — at present — scanty and incomplete as regards the natural processes preceding and accompanying earthquakes.

Information gathered till now by scientists from U.S.S.R., Japan, and U.S.A. points out that both geophysical and geochemical phenomena can act as premonitory events of earthquakes. Geophysics and geochemistry must play a complementary role towards a better understanding of the most important premonitory events, in order to achieve the complete goal in earthquakes forecasting, i.e. to predict both the time and the intensity of earthquakes.

In particular, geochemical studies of deeply circulating waters (e.g. thermal waters) can furnish full information about the thermodynamic and hydrodynamic conditions in depth, as well as about the variation in time of rock-water interaction. And there is a firm link between the above conditions and the physical properties of rock.

In the paper the geochemical results achieved till now are presented, and the role of geochemical methods in confirming or rejecting the different models proposed for earthquakes prediction is discussed.

Finally, the must urgent geochemical investigations to be undertaken in order to reduce our lack of knowledge, and to achieve a higher probability in correctly predicting earthquakes are discussed.

RIASSUNTO. — Negli ultimi anni il mondo scientifico ha maturato la ferma convinzione di poter giungere alla previsione dei terremoti, meta sognata tanto da sismologi che da astrologi. È stato infatti chiaramente dimostrato che numerosi eventi premonitori precedono i terremoti, ma la nostra conoscenza sui processi che precedono i terremoti è purtroppo — allo stato attuale — tremendamente lacunosa.

I dati raccolti da ricercatori della Russia, degli Stati Uniti d'America e del Giappone indicano con chiarezza che tanto i fenomeni geofisici che quelli geochimici possono essere utilizzati come eventi premonitori dei terremoti.

La geofisica e la geochimica possono e debbono giocare un ruolo complementare verso il raggiungimento di una conoscenza più approfondita dei processi naturali che precedono i terremoti al fine di raggiungere pienamente lo scopo, e cioè di predire correttamente tanto il tempo che l'intensità dei terremoti.

In particolare gli studi geochimici delle acque naturali di origine relativamente profonde, come ad esempio le acque termali, possono fornire preziose informazioni sulle condizioni termodinamiche ed idrodinamiche in profondità, così come circa le variazioni nel tempo della interazione acque-rocce. E sussistono relazioni molto strette tra le condizioni sopra citate e le proprietà fisiche delle rocce, e quindi la preparazione del sisma.

Nel lavoro vengono presentati i risultati geochimici ottenuti sin'ora, e viene discusso il

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ruolo che i metodi geochimici possono giocare nell'accettare o nel rigettare uno o l'altro dei differenti modelli proposti per la previsione dei terremoti.

Vengono infine proposte e discusse le ricerche geochimiche più urgenti da intraprendere per giungere ad una più elevata probabilità nel predire correttamente gli eventi sismici.

1. Introduction

All over the world hundreds of scientists now are devoting most their research to earthquake prediction.

Most of this kind of research is being carried out in the U.S.S.R., the U.S.A., Japan, and China, and a wide range of scientific disciplines are involved; from geophysics and geology, to geochemistry and animal behavior.

In the last few years, and for the most part independently in each of the different countries, a real revolution has taken place in our approach to the problem of forecasting earthquakes. All the most qualified scientists have in fact come the convinction that earthquakes are not an unforeseeable disaster, a catastrophe whose tragic consequences have only to be put up with. Instead they are part of the general, continuous dynamics of the earth's crust, and are preceeded by a whole series of premonitory events.

At the roots of this revolution is the acquisition of new experimental data, unexpected until very recent times. These data have shown that several premonitory phenomena, both geophysical as well as geochemical occur anywhere, from a few hours to many years in advance.

In the U.S.S.R., the U.S.A., as well as Japan, medium and strong earthquakes have been predicted on an experimental basis.

But the most stimulating and promising news in the forecasting of earthquakes has been the discovery that, in the area surrounding active faults, the physical properties of the rocks, and also the flow pattern and the composition of ground waters noticeably change before the tectonic movement brings about its catastrophic effects. Earthquakes are prepared by a whole series of geological, geophysical, hydrodynamic, and geochemical processes that begin sometimes even many years before the earthquake starts up; and these can provide us with distinct geological as well as geophysical and geochemical premonitory events.

However we've first got a long way to go before achieving a thorough enough knowledge of the basic processes involved, and before perfecting of our geological, geophysical, and geochemical models.

We mustn't forget, in fact, that the objective of our studies on earthquake prediction concern *where* and *when* they take place, with a reasonable approximation as to their *intensity*.

One last important preliminary problem remains to be examined, and, that is, the real desireability of forecasting earthquakes if we consider from all sides the social impact of such forecasts, keeping in mind the risk we run by a mistaken forecasting, and the possibility of causing social disorders by an improper use of information. Lately it has been heard, and sometimes from authoritative sources, that these negative effects night even be greater than the benefits achieved.

It is this author's opinion that the possibility of forecasting earthquakes is in and of itself a good thing, but we must make absolutely sure not to commit the error of confusing or failing to keep distinct research, surveillance service, and political choices. That such a possibility is in and of itself a good thing is confirmed by the fact that it may be the cheapest, and in some cases the only way, to save a great deal of human lives and the great deal of property that otherwise, on the basis of the expected probabilities of strong quakes in seismic areas, will almost certainly be destroyed by earthquakes in the not so distant future.

Complete seismotectonic studies, besides the possibility of long term forecasting earthquakes, will also have to have the proper place they deserve in the rational planning of land use.

2. Geophysical models in earthquake prediction

Soviet researchers were the first to undertake research on the forecasting of earthquakes.

« Soviet scientists have identified the following premonitory events of earthquakes:

— Mechanical deformation of the earth's surface.

— Increases in the electrical conductivity of the ground. This methods was succesfully used to predict a strong earthquake in the Kamchatka region, along the Bering coast.

— Changes in the chemical composition of groundwater sampled in deep wells, in particular an increase in the radon emitted. This method gave several weeks' warning before two different earthquakes in the Tashkent Region (south-central Asia just north of the Hymalayas).

— Seismological indicators, including an increase in microseismic activity, a change in the orientation of the stress axis in a region, and a shift in the frequency composition of seismic waves from small quakes toward higher frequencies.

— Variations in the ratio of the compressional wave, Vp, to that of the shear wave, Vs in the Garm region. This ratio decreased from its normal value before a quake, then gradually increased, reaching approximately its normal value just before the earthquake » (from: Hammond, 1973).

More recently Japan, as well the U.S.A. and China, have intensified their research on the forecasting of earthquakes and have even reached substantial results in predicting earthquakes on the basis of changes of tilt, seismic velocities and

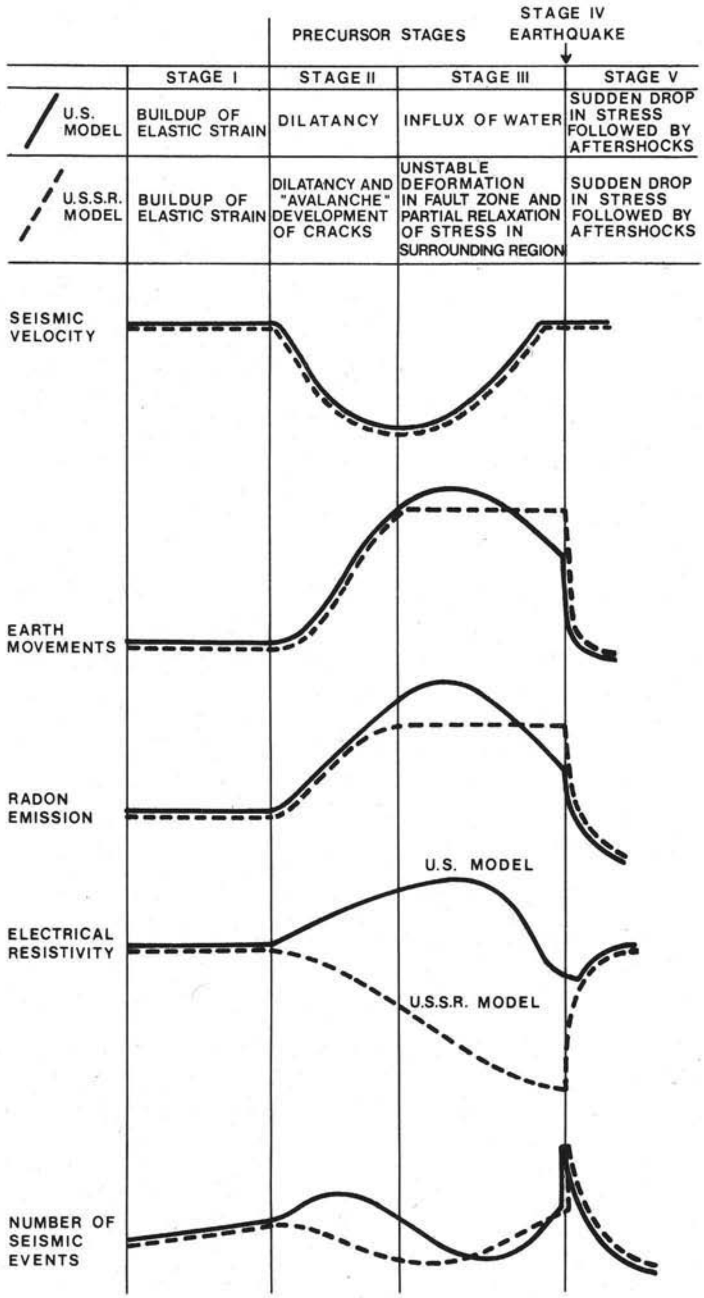

Fig. 1. — Expected precursory events according to the two physical models proposed for earthquake prediction (from: F. Press, 1975).

magnetic fluctuations (Johnston - Mortensen, 1974; Hammond, 1974). From the scientific point of view it is even more important to note that the field and laboratory studies performed in Japan and in the U.S.A., have substantially confirmed the data obtained in the U.S.S.R.

As a result of all these observations an attempt was made to work out a physical model that explains all the observed premonitory events.

The working out of a generally valid model is worthwhile for two different reasons:

- The premonitory events appear to lead to prediction which is *deterministic* rather than *probabilistic*.
- It takes for more efficient research procedures.

Two principal physical models have been proposed: the dilatancy-diffusion theory by A. M. Nur in 1972, and the dilatancy-instability-coalescence model by scientists of the Institute of Physics of the Earth, in Moscow, in 1971.

Here below we provide only a few remarks on the models proposed; we refer to specific publications for greater detail on the subject. (e.g. Nur, 1972; Hammond, 1973; Scholz et Al., 1973).

Briefly, the American dilatancy model takes into account the experimental results on the inelastic changes occurring in the properties of rocks stressed almost to the point of rupture. In particular during this process microcracks and voids appear in the rocks which, moreover, increase in volume. This phenomenon is known as dilatancy. Dilatancy begin when the stress on rocks along a fault, caused by relative movement between crustal plates, reaches half the breaking strength of the rock. The rocks therefore dilate and underground cracks open up. This stage leads to a reduction in pore pressure.

Then ground water flows in from surrounding region and fluid pressure in the rock increases, the shear strength of rock gradually decreases to the point where failure occurs. This point corresponds to an earthquake.

According to the Soviet theory, a buildup of stress in a section of crust produces an avalanche of new cracks in the rocks which gradually align themselves and coalesce, leading to physical failure of the rocks and hence a quake.

The diagrams in Fig. 1 indicate in synthesis how the different premonitory events are to be fitted into the two models proposed for the forecasting of earthquakes. (From F. Press, 1975).

The data gathered up to now doesn't seem to definitely confirm of reject one model or the other.

3. Geochemistry and earthquake prediction. A review

As far as the results achieved till now by geochemical methods are concerned, our information is scarse and incomplete. As a matter of fact the relative importance of geochemical methods is highly variable in the various countries that have costly programs for the forecasting of earthquakes. In the U.S.S.R., and more recently in China, geochemical methods have been widely used, but it's not always easy to get complete information, and-more important-in due time, on the results obtained in these countries. In the U.S.A. geochemical methods have so far received very little attention. Except for the high level research of H. Craig and coworkers in certain areas of California, no systematic use of geochemical methods in this research sector has been heard of.

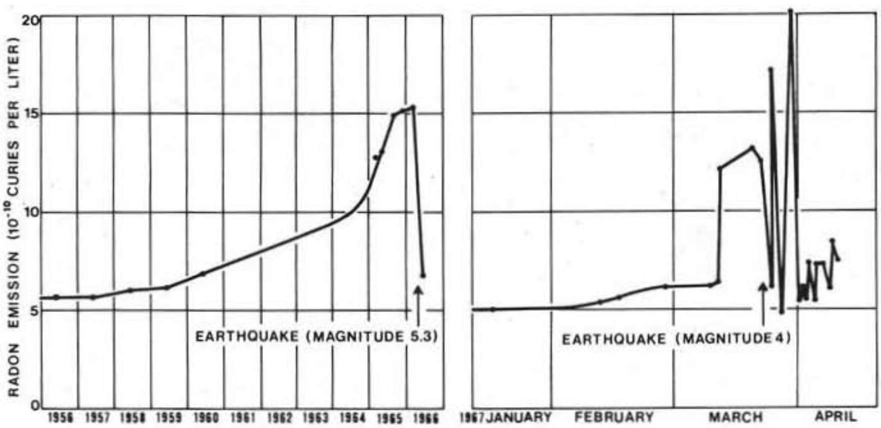

Fig. 2. — Radon content variations in the water of deep wells before two earthquakes in the vicinity of Tashkent (from: F. Press, 1975).

In Japan important geochemical research has been, and still is being carried out, but as far as we know, geochemistry has been far less used than geophysics.

The first news to excite a great deal of interest in geochemical methods in forecasting earthquakes is the sizeable increase found in the radon content in the deep waters some weeks before the Tashkent earthquakes. Fig. 2 shows the variations in the radon content observed before two earthquakes.

A few papers presented at the Symposium on Earthquake Forerunners Searching, Tashkent, 1974, provide a clear idea of how much data were gathered by Soviet researchers, even if it's not always easy to get complete information on all the works done.

In particular Osika, Magomedov, Levkovich and Megaev in their paper « Changing of chemical compounds of mineral waters and gases during strong earthquakes of the northern Caucasus » report that the chemical composition of mineral waters and gases changed both in epicentral zones and at distances of about 100-300 km, before and during strong earthquakes of the Northern Caucasus ». — The constituents that increased considerably were the gases CO_2, N_2, CH_4 and

Rn, and the ions Cl, I, Br, B, Ca and As. The constituents that decreased were H_2S, heavy hydrocarbons, HCO_3, SO_4, Mg, NH_3 and SiO_2.

— « Outflow of gases from the interior to the atmosphere has been noted in the epicentral zone of the Dagestan earthquake. Due to this fact content of H_2 in the air increased by 5-6; the content of CH_4 by 2-3; He by 1.0; CO_2 about one order higher than the Clark one.

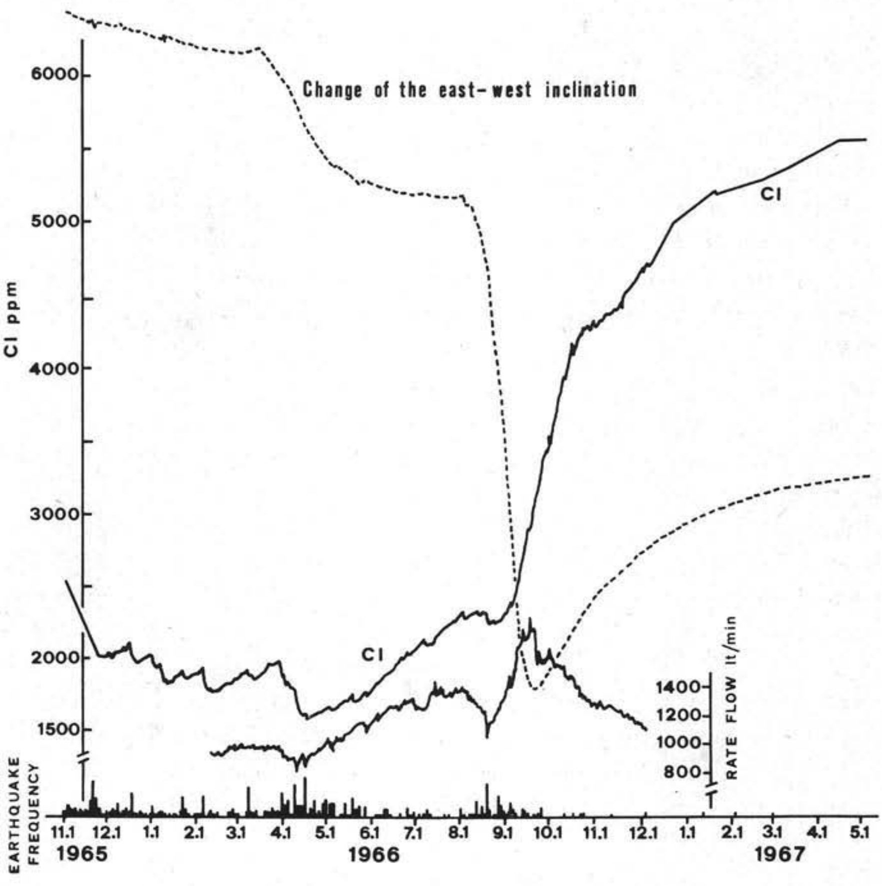

Fig. 3. — Rate flow and Cl content variations in the Kagai Hot Spring Well n. 1 in connection with earthquake swarms (from: Iwasaki, 1975).

— Simultaneous with the changing of chemical composition of water and gases, the increase of temperature of mineral waters by 1-2° has been noted ».

The paper by Mavlyanov, Ulanov and Sulankhodjaev « Earthquake forerunners searching in Uzbekistan » reports « the results of gas contents variation analysis showed that during the periods, preceding large earthquake, the gradual increase of inert gases concentration — helium, radon and others — had been registered ».

In connection with the earthquake there have been ergistered changes in isotopic composition of uranium, helium, argon, in the content of mercury, carbonic acid, and of other elements in underground waters.

Some very interesting information is contained in a Special Issue of the Bulletin Volcanologique now in press, devoted to the publications gathered by a working group of the IAVCEI on the geochemistry of volcanic gases (chairman Nicolai Khitarov).

Iwaji Iwasaki has published a synthesis of the results reached in Japan in the paper « Geochemical Indicators and Seismic Phenomena ».

In this work he stresses the importance of the study of Rn content and of the Tn/Rn ratio in the forecasting both of volcanic eruptions as well as of eartquakes.

Then he discusses the changes in the nature of hot springs and ground waters in connection with the Matsushiro Earthquake Swarn. « This earthquakes swarn occured in and around the Matsushiro town area of Nagano Prefecture, central Japan, from August 1965 to 1968.

As geochemical studies on the nature of hot springs and ground waters began in November, 1965, their precise geochemical nature before earthquake swarn was unknown.

The Kagai Hot Springs showed that discharge amounts of hot springs increased or decreased mainly in connection with the places where the earthquake has occurred, and temperature of hot springs became higher or lower with their discharge amounts. However when the activity of the earthquake swarn entered the third active period (Aug.-Sept. 1966) some of them showed maximum discharge amounts and minimum temperature at the same time. Variations in chemical properties of these waters with time have been studied in detail. For example, Fig. 3 shows the variation of chemical properties of the Kagai Hot Spring Well n.° 1.

According to Kitano et al. (1968) the bulk of ground waters in the Matsushiro area derives from a source deep under the ground which is not directly influenced by precipitation and surface water, the saline waters of a calcium chloride type gush out with the active earthquake swarm and the concentration of calcium and chloride ions in the gushed ground water increase with the activity of the earthquake swarm.

In the same « Special Issue » Markhinin and Boshkova in the paper « Dependence of the chemical composition of thermal waters upon seismic activity » discuss the variations in the composition of thermal waters observed around the Mendeleyev volcano in relation to the earthquake swarm of 1965-66 and the strong earthquake in 1973.

Some variations not very significant were observed and the interpretation is not clear or definitive.

Some papers dealing with earthquake prediction by hydrogeochemical methods will be presented at the Symposium n.° 33 « Thermal and Chemical Problems of Thermal Water » of the I.U.G.G. General Assembly (Grenoble, August 1975).

To conclude this review of the most important pubblication in the field of the earthquake forecasting by geochemical methods one really has to recall the high level research which H. Craig and coworkes are carrying out in certain areas of California (H. Craig et al., 1974, 1975).

This study is focused on the investigations of Radon and Helium as possible fluid-phase precursors to earthquakes.

These studies so far have not come up with any concrete results in earthquake prediction because the period of observation has not yet coincided with any important seismic events in the area surveyed. They however furnish us an excellent example of how research can be set up in order to fully understand the geochemical processes that precede and accompany earthquakes.

Briefly the study is based largely on the analysis of Rn^{222}, of He and of He^4 and He^3. The radon variations observed in deeply circulating waters before the Tashkent earthquake have been attributed to changes either in the rock structure or in the flow pattern of pore water in the dilatant zone (Scholz et al., 1973).

Radon and Helium can play a complementary role for studying fluid-phase effects as possible earthquake precursors. They are infact noble gases and therefore they have no chemistry. Both are added to ground water mainly by radioactive decay. Helium is a stable isotope and therefore it can indefinitely accumulate in a closed system. Radon, on the contrary, has a half-life of only 3.8 days. Sistematic monitoring of both gases should provide a powerful tool for studying the processes occuring in the earthquake regions.

A network of 22 thermal springs and wells has been established along the major faults of Southern California. The major aims of this study are as follows; 1) determining whether radon and helium exhibit precursory concentration variations in these waters, prior to earthquakes, and 2) in a more general sense, the fundamental understanding of the radon-helium relationship in the ground waters of seismic regions.

The program also includes the measurement of dissolved neon and He^3. Neon is not produced in rocks, and He^3 is contained in the atmospheric Helium (1 ppm) and it is, moreover, produced by the decay of tritium.

The determination of these elements and the study of the relationships between them will let us get a clear idea of the processes that take place in connection with earthquakes and with the variation in time of the flow pattern of pore water, taking into account at the same time the atmospheric and the crustal origin of the different isotopes above considered.

The Laboratory of Environmental Geochemistry of the CNEN, for over a year now, has been working on the systematic study of certain Italian hydrothermal systems in seismic zones, in different structual, litholgical and seismic situations; and, that is in the zones of Tuscania (Northern Latium) the Gargano Promontory (Apulia Region), Western Sicily, and the Campi Flegrei near Naples. The study emphasizes a systematic monitoring of the following parameters in the thermal waters; the major constituents dissolved, F, B, U, NH_3, Rn, Li, Rb, Cs and U^{234}/U^{238}. We are, moreover, working out a battery operated field instrument for the continuous monitoring of the Rn content and of temperature and electrical conductivity values.

In the next future it is hoped that a systematic study can also be made of He and of the other rare gases.

So far direct indications have not been obtained, since in the zones studied no strong earthquakes have occurred, nor have variations in the composition of the waters examined.

4. The role of geochemistry in forthcoming studies

In the preceding section a review was made of the most important results already obtained, and of the research in progress on earthquake forecasting by geochemical methods.

At this point we might look over the main problems to be solved in order to improve the reliability of our forecasting, as well as in order to get a better understanding of the basic geological and geochemical processes connected with earthquakes. The latter scientific aspect also influences directly, or inderectly the practical applications and the reliability of the decisions to be made.

The questions that require thorough going answers are:

1. Is the dilatancy-diffusion model always valid? In other words are there earthquakes that are not preceded by appreciable dilatancy phenomena?
2. How far from the active fault does the dilatancy area go, and how far premonitory phenomena can be detected?
3. How precisely and how far in advance can we determine when, where, and how intense the earthquake will be.
4. What methods are the most promising for earthquake forecasting under the widely varying structural, lithological, seismic, and environmental conditions found in the various areas of the globe worst hit by earthquakes.
5. What can be said, in particular, about forecasting earthquakes with respect to active volcanic zones and earthquake swarms?

The first question is perhaps the most important, because it deals with the philosophy on which an approach to the problem and research planning are based. In the case of earthquake prediction there is once more the ever-present dilemma of geological science, and, that is, if a model can manage to include in its structure all the widely varying conditions come across in nature, and every possible combination and interaction between them.

One particular advantage of having a valid model is that forecasting becomes deterministic rather than probabilistic.

The research carried out so far has not been sufficient to confirm or reject the general validity of the dilatancy-diffusion model. According to SCHOLZ et al. « The dilatancy instability appears to account for the entire class of long-range earthquake precursors yet observed. It thus seems commonly applicable in at least some types of tectonic regimes, for example, those involving a significant component of thrust faulting and those where complications or conditions exist such as to allow the stress to rise to high values. It is possible that stresses along simple strike-slip faults such as in central California will not rise high enough to initiate dilatancy, however, the Danville earthquake, which was preceded by anomalous tilts, had a strike-slip mechanism.

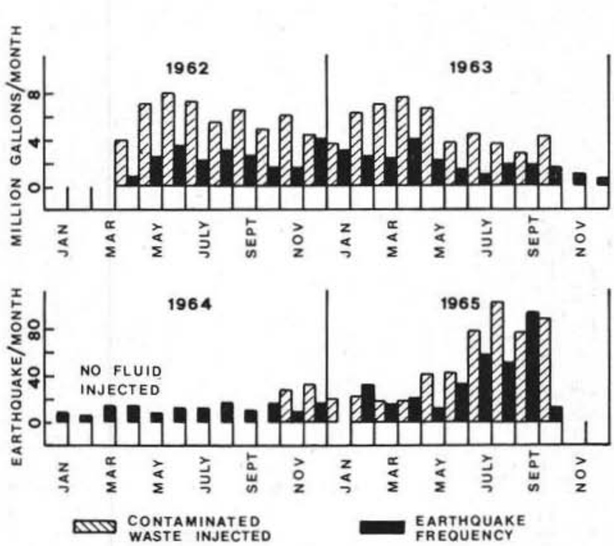

Fig. 4. — Correlation of number of earthquakes with amounts of fluid injected in well, Rocky Mountain Arsenal (from: Johnston et al., 1974).

We suggest that the dilatancy mechanism is an instability from which there is apparently no return to stage I whithout the occurrence of an earthquake. In this sense dilatancy and fluid flow cause or trigger the earthquake ».

JOHNSTON et al. (1974) also maintain that earthquakes are not always preceded by noticeable dilatancy phenomena. The earthquakes triggered in Colorado by the injection of waste fluids into the crystalline basement rocks in a well 3.7 km deep provide us with supplementary information in this regard. Fig. 4 gives the diagram: waste fluid injection versus earthquake frequency, over a period of 4 years. It is to be stressed that the area considered was previously seismically quiet. (JOHNSTON et al., 1974).

In the case given the direct cause of the earthquake seems to be the in-depth injection of fluids. It is therefore resonable to suppose that natural processes can also bring about variations in the hydrodynamic conditions, and thus in the physico-chemical properties of the rocks, capable of triggering earthquakes in much the same way as the one in Colorado was by waste fluid injection.

Another case in which it's hard to assume the full validity of the dilatancy model is for earthquake swarms and earthquakes connected with active volcanoes.

Even however, if we have not certainly valid model, the problem of earthquakes forecasting can be all the same solved by a more empirical approach, by discovering all the premonitory events that always precede earthquakes.

TABLE 1

Changes in chemical composition observed in some thermal springs from western Sicily after the 1968 earthquake

	MUD VOLCANO "MOLINI"	SCIACCA THERMAL SPRING			MONTEVAGO SPRING		
Date of Sampling	27.2.68	2.7.65	28.2.68	28.4.69	24.11.65	27.2.68	28.4.69
T °C	15	approximately 55			31	33	35
pH	7.8	6.0	5.7	5.4	7.0	6.8	6.7
Ca	0.52	64	70	61	6.6	8.9	8.1
Mg	1.0	33	36	36	4.2	5.6	8.1
Na	55	240	300	280	4.3	6.5	6.3
K	0.97	9.0	9.2	9.0	0.26	0.36	0.38
HCO_3	21	6.4	8.6	8.5	3.9	4.2	3.9
SO_4	2.9	9.8	10	13	5.4	8.1	11
Cl	34	370	410	370	5.1	9.3	8.5
SiO_2	0.12	1.6	0.67	0.68	0.31	0.36	0.39
F	14	4.4	25	21	7.9	9.0	9.4
B	52	210	220	200	1	4.2	3.2

(shaded) AFTER EARTHQUAKE

In the first column is shown the composition of the water collected in a mud volcano originated by the seismic muovement (chloride and sodium bicarbonate chemism). The changes observed in the other springs correspond to a mixing of the normal water with a mud type water (Sciacca spring), and to an increase of the content of more soluble salts. Notice the large variation in pH and temperature values.

Since there is no strict causal link between premonitory events and eartquake, instead of being deterministic forecasting tend to be probabilistic. In this way the part that is lost in efficiency is more than made up for by the wider range of applicability of the forecasting methods.

Improving and extending our geochemical studies can stimulate both the discovery of a wide range of premonitory events-perhaps even some as yet unexpected-, and also bring us to a better understanding of the geochemical processes that are connected with earthquakes. This knowledge will help us make our forecasting more and more deterministic, and hence more and more efficient.

From what has been said above both in the discussion of the dilatancy models and in the presentation of the studies and observations made all over the world, it becomes clear that the circulation of fluids or rather variations in the hydrodynamic conditions and pore pressure in time are the basic process that trigger earthquakes. In more general terms, as the crustal movement more or less slowly prepare the ground for the sudden release of the destructive energy of the quake, substantial modifications must take place in the water-rock interaction.

We are familiar with many aspects of water-rock interaction in different lithological environments and under different physico-chemical conditions; we are familiar, moreover, with the mineral equilibria corresponding to various conditions, but we must admit our lack of knowledge about the variations in time of the water-rock interaction processes before earthquakes.

This depends upon the scanty and incomplete experimental data on this subject. The changes observed in the water chemistry of some thermal springs in the Belice Valley (Western Sicily) after the earthquake of February, 1968 are shown in Table 1 (DALL'AGLIO, 1970).

These data indicate that the content of some major constituents dissolved, as well as the temperature and pH values, varied a great deal.

Anyone familiar with hydrogeochemistry will understand clearly how much the underground condition must have varied in connection with earthquake to bring on such substantial variations in the chemism in a spring with a flow rate higher than 100 l/s.

On the basis of theoretical considerations and also of the little experimental data available, important variations in the water-rock interaction must occur even before the tectonic movement becomes a quake.

In the field of earthquake forecasting studies, geochemical research is required to solve two kinds of problems and that is:

1) How to improve our knowledge of the ground processes occurring in connection with earthquakes.
   An excellent example of how the research must be planned in order to better understand the flow pattern and the pore pressure variations in time, is given by the research undertaken by H. Craig and coworkers in California, already briefly described above. Studies of this type can provide results valid not only from a geochemical viewpoint, but also in confirming or rejecting one or the other of the particular models proposed. See e.g., the discussion about the variations in He and Rn contents, expected according to the dilatancy-diffusion model (CRAIG et al., 1974). It should be emphasized that research of this type must be closely coordinated with geological and geophysical studies, and presupposes the use of high level geochemical technology.

2) How to discover all the hydrogeochemical events that can be used, to some good as premonitory events for earthquakes. In this sector a great deal remains to be done, and, on the basis of our present knowledge we cannot even indicate

a precise order of priority in the studies to be undertaken.

These studies must, however, be based on observations to be carried out over years and even decades, and must include geological, environmental, and seismic situations different from one another. It must not be forgotten that the slow deformations in the crust that precede earthquakes bring about substantial variations not only in the hydrodynamic conditions of the ground, but also in the circulation pattern and in the mixing processes of the shallow aquifers and of the surface waters with thermal waters.

Notice e.g. the high variations in Cl content presented by Iwasaki (1975) in connection with earthquake swarms.

Many geochemical indicators are quite suited to show variations of this type, but it is very hard to plan such a research in a very efficient way, because we don't know enough about the premonitory geochemical processes to permit us, at present, to answer with any certainty even simple questions like the following. Is it more useful to have simple continuous monitoring systems for let's say just temperature and electrical conductivity in ten different springs, or only one station for the analysis of all the most important geochemical parameters together? The fact that we cannot give a definite answer means, as a matter of fact, that both types of research are helpful in reducing our lack of knowledge. Anyway extending and improving geochemical studies are sure to provide us with thorough answers to many of the questions posed previously.

5. Conclusions

In this paper we have reviewed the most recent results achieved in the forecasting of earthquakes and have examined the contributions by various disciplins, and in particular by geochemistry, to the solving of this new scientific problem, which has political and social implications too.

Geochemical methods have clearly proved they can provide useful information for earthquake forecasting.

So far, however, very little attention has been paid to geochemical studies as compared to geophysical and geological ones. The potential role of geochemical studies is nonetheless enormous because they can clarify our understanding of what really happens underground in connection with earthquakes, and also because they may indicate a whole new series of premonitory events to use in forecasting earthquakes.

Geochemical studies should include further research on the in-time variations in the water-rock interaction processes and in the ground thermodynamic conditions; they also should include extensive research on new areas and on a large number of geochemical parameters over long periods of time.

We might attempt to suggest a list of research projects that might be undertaken or intensified.

1) The study should be emphasized of all those geochemical parameters that might provide information on flow pattern and pore pressure variations, like Rn, He, rare gases etc.
2) The studies should be intensified of the elements and compounds that may provide information on thermodynamic conditions in the ground, an on the water-rock interaction processes such as Li, Rb, Cs, NH_3, H_2S; besides, of course, the major constituents.
3) We should extend our observations to new areas and over long periods of time for the simpler parameters to be determined such as temperature, flow rate, electrical conductivity, and pH.
4) We should study the use of remote sensing (for example mounted on satellites) to recording variations in the way thermal waters come to the surface, and/or variations in the temperature values.
5) We should keep up with the geochemical studies on geothermal fields.
6) We should keep up with geochemical research on the forecasting of volcanic eruptions (See. e.g. UNESCO, 1972).

We are still left with the basic problem of the insufficient support to geochemical research on earthquake forecasting, as compared to the quantity and quality of the research that still has to be carried out, or undertaken.

The better utilization of the limited resources made available supposes above all a closer collaboration between the various disciplines and between the different countries.

Expecially in such a new field of investigation a rapid and complete exchange of information on results, as they are reached in the various countries, may turn out to be more effective than an increase in financial support.

Given the scope of the studies to be carried out, an international planning of research should be necessary to get more rapid and more complete results.

It is also to be hoped that International Research Organizations, and first of all the I.A.C.G., look into this problem and make the contributions only they can toward the rapid progress of science at the service of the whole world community.

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