COMITATO NAZIONALE ENERGIA NUCLEARE

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NUCLEAR SAFETY DIVISION

Proceedings of Specialist Meeting on
THE 1976 FRIULI EARTHQUAKE
AND THE ANTISEISMIC DESIGN
OF NUCLEAR INSTALLATIONS

Rome, Italy, 11-13 October 1977

VOLUME 1

May 1978
COMITATO NAZIONALE ENERGIA NUCLEARE

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THE 1976 FRIULI EARTHQUAKE AND THE ANTISEISMIC DESIGN OF
NUCLEAR INSTALLATIONS

Rome, Italy, 11-13 October 1977

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COMITATO NAZIONALE PER L'ENERGIA NUCLEARE

in cooperation with the

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VOLUME I

Opening Session

Session I.a - Geotectonic, Geophysical and Seismological
aspects: Geotectonics.

Session I.b - Geotectonic, Geophysical and Seismological
aspects: Geophysics and Seismology.

May 1978
The Organisation for Economic Co-operation and Development (OECD) was set up under a Convention signed in Paris on 14th December, 1960, which provides that the OECD shall promote policies designed:

— to achieve the highest sustainable economic growth and employment and a rising standard of living in Member countries, while maintaining financial stability, and thus to contribute to the development of the world economy;

— to contribute to sound economic expansion in Member as well as non-member countries in the process of economic development;

— to contribute to the expansion of world trade on a multilateral, non-discriminatory basis in accordance with international obligations.

The Members of OECD are Australia, Austria, Belgium, Canada, Denmark, Finland, France, the Federal Republic of Germany, Greece, Iceland, Ireland, Italy, Japan, Luxembourg, the Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States.

The OECD Nuclear Energy Agency (NEA) was established on 20th April 1972, replacing OECD's European Nuclear Energy Agency (ENEA) on the adhesion of Japan as a full Member. NEA now groups eighteen European Member countries of OECD and Australia, Canada and Japan, with the United States as an Associated country. The Commission of the European Communities takes part in the work of the Agency.

The objectives of NEA remain substantially those of ENEA, namely the orderly development of the uses of nuclear energy for peaceful purposes. This is achieved by:

— assessing the future role of nuclear energy as a contributor to economic progress, and encouraging co-operation between governments towards its optimum development;

— encouraging harmonisation of governments’ regulatory policies and practices in the nuclear field, with particular reference to health and safety, radioactive waste management and nuclear third party liability and insurance;

— forecasts of uranium resources, production and demand;

— operation of common services and encouragement of co-operation in the field of nuclear energy information;

— sponsorship of research and development undertakings jointly organised and operated by OECD countries.

In these tasks NEA works in close collaboration with the International Atomic Energy Agency, with which it has concluded a Co-operation Agreement, as well as with other international organisations in the nuclear field.

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L'Organisation de Coopération et de Développement Économiques (OCDE), qui a été instituée par une Convention signée le 14 décembre 1960, à Paris, a pour objectif de promouvoir des politiques visant :

- à réaliser la plus forte expansion possible de l'économie et de l'emploi et une progression du niveau de vie dans les pays Membres, tout en maintenant la stabilité financière, et contribuer ainsi au développement de l'économie mondiale ;
- à contribuer à une saine expansion économique dans les pays Membres, ainsi que non membres, en voie de développement économique ;
- à contribuer à l'expansion du commerce mondial sur une base multilatérale et non discriminatoire, conformément aux obligations internationales.

Les Membres de l'OCDE sont : la République Fédérale d'Allemagne, l'Australie, l'Autriche, la Belgique, le Canada, le Danemark, l'Espagne, les États-Unis, la Finlande, la France, la Grèce, l'Irlande, l'Islande, l'Italie, le Japon, le Luxembourg, la Norvège, la Nouvelle-Zélande, les Pays-Bas, le Portugal, le Royaume-Uni, la Suède, la Suisse et la Turquie.


Les objectifs de l'AEN restent pour la plupart les mêmes que ceux de l'EEA et concernent la promotion du développement harmonieux des utilisations pacifiques de l'énergie nucléaire. Elle entreprend à cet effet :

- d'évaluer le rôle futur de l'énergie nucléaire dans la réalisation du progrès économique et d'encourager la coopération entre les gouvernements en vue de son développement optimal ;
- de promouvoir une harmonisation des politiques et pratiques réglementaires des gouvernements dans le domaine nucléaire, en particulier pour la protection de la santé et la sécurité, la gestion des déchets radioactifs, la responsabilité civile et l'assurance en matière nucléaire ;
- d'établir des prévisions sur les ressources, la production et la demande d'uranium ;
- d'assurer le fonctionnement de services communs et d'encourager la coopération dans le domaine de l'information nucléaire ;
- de patronner des entreprises de recherche et de développement organisées et exploitées en commun par des pays Membres de l'OCDE.

Pour remplir ces fonctions, l'AEN travaille en étroite collaboration avec l'Agence Internationale de l'Énergie Atomique (avec laquelle elle a conclu un accord de coopération) ainsi qu'en liaison avec d'autres organisations internationales dans le domaine nucléaire.

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2, rue André-Pascal, 75775 PARIS CEDEX 16, France.
The NEA Committee on the Safety of Nuclear Installations (CSNI) is an international committee made up of scientists and engineers who have responsibilities for nuclear safety research and nuclear licensing. The Committee was set up in 1973 to develop and co-ordinate the Nuclear Energy Agency's work in nuclear safety matters, replacing the former Committee on Reactor Safety Technology (CREST) with its more limited scope.

The Committee's purpose is to foster international co-operation in nuclear safety amongst the OECD member countries. This is done essentially by:

(i) exchanging information about progress in safety research and regulatory matters in the different countries, and maintaining banks of specific data; these arrangements are of immediate benefit to the countries concerned;

(ii) setting up working groups or task forces and arranging specialist meetings, in order to implement co-operation on specific subjects, and establishing international projects; the output of the study groups and meetings goes to enrich the data base available to national regulatory authorities and to the scientific community at large. If it reveals substantial gaps in knowledge or differences between national practices, the Committee may recommend that unified approach be adopted to the problems involved. The aim here is to minimise differences and to achieve an international consensus wherever possible.

The technical areas at present covered by these activities are as follows: particular aspects of safety research relative to water reactors and fast reactors; probabilistic assessment and reliability analysis, especially with regard to rare events; siting research as concerns protection against external impacts; fuel cycle safety research; the safety of nuclear ships; various safety aspects of steel components in nuclear installations; licensing of nuclear installations and a number of specific exchanges of information.

The Committee has set up a sub-Committee on Licensing which examines a variety of nuclear regulatory problems, provides a forum for the free discussion of licensing questions and reviews the regulatory impact of the conclusions reached by CSNI.
IV

Le Comité de l'AEN sur la Sûreté des Installations Nucléaires (CSIN) est un comité international composé d'hommes de science et d'ingénieurs qui sont investis de responsabilités en matière de recherche sur la sûreté nucléaire et d'autorisation des installations nucléaires. Le Comité a été institué en 1973 en vue de développer et de coordonner les travaux de l'Agence pour l'Energie Nucléaire dans le domaine de la sûreté nucléaire. Il remplace l'ancien Comité des Techniques de Sécurité des Réacteurs (CREST), dont les compétences étaient moins étendues.

Le Comité a pour but de stimuler la coopération internationale en matière de sûreté nucléaire parmi les pays Membres de l'OCDE. Les moyens mis en œuvre à cet effet sont essentiellement de deux ordres:

(i) des échanges d'informations sur les progrès de la recherche en matière de sûreté et sur les questions de réglementation dans les différents pays et la constitution de banques de données spécifiques; ces dispositions présentent un avantage immédiat pour les pays intéressés;

(ii) la création de groupes de travail ou de groupes spéciaux et l'organisation de réunions de spécialistes, de manière à établir une coopération sur des sujets déterminés et à mettre sur pied des projets internationaux. Les résultats obtenus par les groupes d'études et par les réunions enrichissent la base de données dont disposent les autorités nationales chargées de la réglementation et la communauté scientifique dans son ensemble. S'il se révèle des lacunes importantes dans les connaissances ou des différences entre les pratiques nationales, le Comité peut recommander l'adoption d'une approche unifiée des problèmes considérés. Le but visé est, dans ce cas, de réduire au minimum les divergences et d'arriver à un consensus international chaque fois que c'est possible.

Les activités du Comité s'étendent actuellement aux domaines techniques suivants: aspects partiuliers des recherches en matière de sûreté dans le cas des réacteurs à eau et des réacteurs rapides; évaluation probabiliste et analyse de fiabilité, particulièrement en ce qui concerne les événements rares; recherche en matière d'implantation dans ses rapports avec la protection contre les impacts d'origine externe; recherche sur la sûreté du cycle du combustible; sûreté des navires nucléaires; différentes questions de sûreté relatives aux composants en acier des installations nucléaires; autorisation des installations nucléaires et un certain nombre d'échanges spécifiques de renseignements.

Le Comité a mis sur pied un Sous-Comité chargé des questions relatives aux autorisations, qui aborde différents problèmes de réglementation en matière d'installations nucléaires, constitue un lieu privilégié pour la libre discussion des questions d'autorisation et procède à l'examen de l'incidence sur la réglementation des conclusions formulées par le CSIN.
In publications, reference to the proceedings of this Meeting should be made as follows:


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Appendix 1

Conclusions and recommendations of the specialist meeting of the 1976 Friuli earthquake and the antiseismic design of nuclear installations (by the Chairman of the Meeting, Prof. M. Mittempergher).

Appendix 2

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Appendix 3

Programme of the Meeting and List of Programme Committee Members
INTRODUCTION

The present volume collects the proceedings of the "Specialist meeting on the 1976 Friuli earthquake and the antiseismic design of nuclear installations", promoted by NEA with the technical and organisation support of the Italian Nuclear Energy Committee (CNEN) and the Italian Electricity Generating Board (ENEL). The meeting was held in Rome, October 11-13, 1977.

The aims which suggested the organisation of the Meeting and the results expected from the discussions are fully illustrated in the opening addresses reported as foreword to the volume. In the same part of the volume the objectives of NEA activities in the field of nuclear safety and the respective roles of CNEN and ENEL in carrying out advanced seismologic investigations with reference to the selection of nuclear sites and the design of nuclear plants are also reported in details.

It seems therefore more advisable, here, to supply the reader with some information and explanations about the actual editorial action concerning the volume. CNEN willingly charged itself with the publication of the proceedings of the Meeting; priority has been given to the necessity of diffusing in the shortest possible time the scientific material related to problems rapidly evolving and at the same time requiring an immediate application to the antiseismic practice.

This is the reason why CNEN has been obliged to reproduce directly the papers presented by the Authors, without attempting any editorial intervention aiming at a standardization of the texts and an improvement of the language selected by each Author.

Consequently the Authors are fully responsible also for the formal aspects of their scientific contributions. CNEN, however, is sorry not to have been able to conclude with a more elegant and editorially improved volume a Meeting which has been rich for the personal participation of many experts, for the scientific contributions, and for the operative conclusions.
OPENING REMARKS, WELCOME ADDRESSES
OPENING ADDRESS BY PROF. A.M. ANGELINI
ENEL PRESIDENT

I am delighted to welcome on ENEL's behalf the participants in the Conference on the Friuli earthquake and on the antiseismic design of nuclear power stations that takes place here in our auditorium, starting to-day, October 13, under the sponsorship of the Committee for Nuclear Plant Safety, of the OECD Agency for Nuclear Energy, of the Comitato Nazionale per l'Energia Nucleare and of ENEL. I wish to thank all the participants, particularly the foreign participants, who are all authoritative and highly qualified persons in this field. Special thanks to Prof. Mittempergher of CNEN, who will chair this conference.

The problems associated with seismicity, especially when seismic manifestations are likely to occur that will affect the social and economic development of the country considerably, call for a broad and deep understanding of the local geodynamic situation. Such an understanding is even more important in selecting nuclear plant sites, in view of the stringent safety requirements for the construction and operation of these stations. In view of the peculiar geodynamic situation in our country, research programs have been launched time ago, including systematic studies on the geology and history of seismicity on one hand and on the other hand the setting up of appropriate means to acquire instrumental data. So the catastrophic earthquake that struck Friuli in 1976 did not find us unprepared; in fact, of all the earthquakes that have occurred in Europe over the years, it is the one in which we have been able to collect the largest number of experimental and instrumental data. This has been possible thanks to the network of accelerographs that ENEL had set up over the whole national territory under the above-mentioned program and which was in perfect working order at the time of the Friuli earthquake, and because of the prompt intervention by ENEL, CNEN, the National Institute of Geophysics, the National Research Council, the Geophysical Observatory of Trieste and others, who reached the area with additional suitable instrumentation.

The purpose of this conference is to provide an overall picture of the information gathered so far from the studies underway on the Friuli earthquake and on the lessons to be acquired for the purpose of antiseismic design of nuclear power stations. The conference focuses on the geotectonic, geophysical and seismological aspects, on the behaviour of the soil, on the interaction of the soil and structures, on the behaviour of the structures and on the assessment of the seismic risk. A great deal of activity is underway in Italy on these matters and ENEL is engaged to the maximum extent allowed by its terms of reference.

I thank you for your attention and express my regret that I will not be able to attend the conference throughout because of other urgent business.

I now give the chair to Prof. Mittempergher.
OPENING ADDRESS BY PROF. M. MITTEMPELNGHER
CNEN

In my quality of Chairman of this Meeting, I am pleased to address a heartful welcome to all the participants and our thanks for having accepted the invitation of NEA to be present and give life to this meeting. My thanks are particularly dedicated to the guests coming from abroad and especially to the scientists who crossed the Atlantic to share our work.

As all of you know, the merit of deciding to organize this meeting has to be attributed to the Committee on the Safety of Nuclear Installations of the Nuclear Energy Agency. The Committee timely interpreted the increasing requirement of supporting with more data and with new field experience the evaluation criteria of the seismic phenomena with reference to the selection of the areas for nuclear plants and to the design of the plants themselves.

The Committee suggested, to this purpose, to use the results of the several investigations carried out during the seismic period in Friuli. This seismic period, started in May 1976, in fact, besides having represented a severe tragedy for our Country, constituted and still constitutes an extremely rich source of information and of data, which are of the utmost importance for a better understanding of the phenomena, but also for improving the conceptual and operative approaches to the antiseismic practice.

The suggestion of the Nuclear Energy Agency found the maximum availability of the Italian Electricity Board (ENEL) and of the Italian Committee for Nuclear Energy (CNEN), which willingly accepted to give an operative feature to the organization of this meeting. Both CNEN and ENEL, engaged according to the law in the field of the nuclear development, even if with different tasks, have always been very sensitive in front of the seismic problems related to the siting of nuclear plants and to the safety of the plants themselves. This is shown by the fact that, through the promotional and coordinating activity of an ENEL-CNEN Commission, the two agencies started wide research action on the whole national territory and intervened in the seismic area of Friuli with a great variety of interests.

In my quality of Chairman of this meeting and of CNEN employee, I would like to thank ENEL, which hosts us in this moment, addressing the thanks of all the audience to Prof. Angelini who honoured us with his presence.

Dr. Ilari as representative of NEA will describe more in details what is expected from the works of the meeting. On my part, I would only stress the motives which suggested to the Program Committee of the meeting the topics appearing in the programme of these study days. The selection of the topics has been based on the opinion, confirmed by the studies of the Friuli earthquake, that only very detailed and exact studies on the different aspects of the geodynamic manifestations, permit to carry out correct evaluations
of seismic safety of nuclear plants. In particular, the relevance of the naturalistic components is determining in the geologic and geodynamic conditions of our Country, where a great variety of local situations does not allow automatic extrapolations, especially when the aim of rationally using the territory includes the siting of nuclear activities.

Consequently, the works of this meeting will be focussed on the more specific problems of the nuclear seismic safety, such as those of the seismic risk referred both to the site and to the plants, only after a careful examination of the different parameters: geological, seismologic, accelerometric, of behaviour of structures and soil dynamics. To offer a possibility of synthesis of all the meeting, a final session devoted to a panel discussion has been foreseen.

The programme of the meeting foresees, moreover, in its opening day, an introductory session. In our intentions, this session should represent a manifestation of dutiful information especially dedicated to our colleagues from abroad and more generally to all those persons who did not live, first hand, the experience of the seismic period in Friuli. In this introductory session we shall give a general outline of the phenomenon and of its effects, so that the works of the meeting could develop from a reference cognitive support. The first part of this information session will supply us with the objective data of the phenomenon; a second part should give you a synthetical vision of the effects of the earthquake. We used, for this, a film representing the best we were able to find out in the field of the commercial diffusion of information. The third part, at last, has been entrusted to the synthesis ability and experience of Prof. L. Ogniben, who will outline the geologic picture at continental level within which the sector of the alpine chain, site of the seismic phenomena under study, has to be placed.

Before ending this short introduction of mine, let me express the wish that out work could actually and operatively contribute to increase not only the nuclear safety standards, but also the degree of confidence and of awareness with which it is necessary to afford the technical and psychological problems characterizing the impact between nuclear installations and the environment.

This wish of mine intends to call to the attention of us all the social aims, which are as important as the technical and scientific ones, of the meeting. Thank you very much.

I have now the pleasure of inviting Dr. Ilari to speak on behalf of the Nuclear Energy Agency.
OPENING ADDRESS BY DR. O. ILARI
OECD/NEA

Professor Angelini, Professor Mittempergher, Ladies and Gentlemen,

I am pleased to welcome you on behalf of the Director General of the OECD Nuclear Energy Agency to this CSNI Specialist Meeting on the Friuli earthquake and the antiseismic design of nuclear plants. It also gives me pleasure to transmit to you best wishes from the Chairman of the Committee on the Safety of Nuclear Installations (CSNI) for a successful meeting.

Over the past four years this Committee of NEA has sponsored some 20 Specialist Meetings and various other co-operative activities in the field of nuclear safety research and regulatory matters.

Because of the marked multidisciplinary character of this meeting, I think it would be perhaps appropriate to speak a few words about CSNI and its role in international co-operation.

The merits of the international co-operation in nuclear safety and regulatory matters are today, I believe, undisputed. Let me just recall briefly the three fundamental reasons for this:

1. There is a clear need for the different countries to compare experience and share the effort involved in reducing the risks associated with nuclear power and in maintaining its excellent safety record.

2. Safety and regulatory questions are especially well suited for intergovernmental co-operation - such as is carried out in the framework of NEA - as these questions are the primary responsibility of public bodies in our Member countries.

3. Visible and vigorous international co-operation in nuclear safety leading to a consensus on important safety questions is likely to ease public acceptance of nuclear power.

In the light of these basic incentives for international co-operation, the first concerted effort by the NEA in the field of nuclear safety developed within the then CREST, or Committee for Reactor Safety Technology, as from 1965. As it was appropriate at that time, this Committee was concerned with those basic aspects of nuclear technology affecting reactor safety. In 1973 the present Committee on the Safety of Nuclear Installations, or CSNI, was set up, in order to expand the co-operation between Member countries in nuclear safety research and also to provide a forum for a free exchange of information and views between national regulatory and licensing authorities.

CSNI brings together the most influential voices in nuclear safety research and licensing in the OECD area, and its working objectives are essentially two:
- to enrich and broaden, by means of technical exchanges, the fund of data available to designers and to regulatory authorities for taking their decisions in the matter of safety;

- to achieve consensus of experts and responsible people on key safety issues.

With these aims in mind, a flexible working arrangement has been adopted as follows:

- CSNI meets in plenary session, usually once a year, primarily for setting up direct co-operative ventures in safety research, and to co-ordinate relevant national work;

- under CSNI direction special studies are carried out by a number of groups of experts, working groups and task forces, or through specialist meetings;

- results and conclusions are subsequently reported and evaluated by CSNI and, through its national delegates, they are diffused to national safety authorities.

It is probably appropriate to recall and point out that this effort of CSNI, by its very nature and its objectives, is focussed on the solution of selected advanced problems and in no way can it be confounded with the development of safety codes or guides, which is a specific responsibility of the IAEA. We can even say that, contributing to the broadening of the safety data base, the CSNI programme is complementary with that of IAEA and in fact we strongly support the IAEA activities in this field.

I need not remind you of the spectacular expansion of nuclear safety activities in the OECD area in recent years. This development has been accompanied by an even stronger increase in international contacts and collaboration.

Let me just give you a few figures to illustrate the importance of nuclear safety in terms of money in the OECD area. Our Member countries spend some 15-20 billion dollars annually to construct and operate nuclear power plants and the associated fuel cycle facilities. At the same time expenditure of OECD governments on safety research amounts to about 800 million dollars a year, and this sum is divided among some 1100 different research projects: these projects are listed and described in the CSNI Nuclear Safety Research Index, which is published annually.

Obviously, CSNI's contribution to such a complex programme is necessarily restricted to those questions judged most important and urgent by a sufficient number of Member countries. While it is important to be as comprehensive as possible in the area of general information exchange - such as the Nuclear Safety Research Index - the limitation of resources, both nationally and internationally, dictates that operational co-operation on specific topics such as pursued by CSNI ancillary bodies (working groups, task forces, etc.) must be limited to those which have been accorded highest priority. In this respect CSNI produced last year a list of priority topics on which to base its future programme. This list includes some 70 specific questions grouped
in four broad areas covering safety research and a fifth area pertaining to regulatory and licensing matters. These areas are as follows:

- Thermal reactor safety research, including such topics as emergency core cooling problems, international comparisons of computer codes for the analysis of loss of coolant accidents, fuel behaviour in accident conditions, etc.

- Fast reactor safety, covering subjects such as sodium/fuel interactions, aerosol behaviour in accident conditions, etc.

- Fuel cycle safety, with problems such as UF6 behaviour in accident conditions, fire and explosion problems and prevention, loss of cooling accidents in high level waste storage tanks, etc.

- General safety, including the safety of nuclear ships, the definition and treatment of rare events in the probabilistic safety assessments, the mechanical and material problems of steel components of power reactors, etc.

A special field of activity in this last area is siting research, with particular reference to the external impacts on the safety of nuclear plants. One fundamental part of this programme concerns the natural impact connected with seismic phenomena.

This matter was the object of the attention of CSNI from its beginning. In previous years international co-operation was carried out gathering together most of the highly reputed national experts in the fields of seismology and seismotectonics, soil and structural engineering and antiseismic design of nuclear plants, in two Specialist Meetings held in Pisa in 1972 and in Paris in 1975. The reports presented at those meetings and the associated discussions contributed to an harmonized progress of knowledge and, above all, they allowed the identification, by a highly representative international audience, of the fields where a better knowledge was necessary and of the problems of interpretation and methodologies still to be solved for a satisfactory seismic assessment of nuclear sites and plants and antiseismic design of the plants themselves.

After this first phase, a more vigorous development was impressed this year through two diversified, but co-ordinated, initiatives. The first was the set-up of an Expert Group, including specialists coming from nine countries and the CEC, charged with studying some of the most controversial and key problems identified by the previous Specialist Meetings, and with preparing a report for CSNI on the state-of-the-art and the possible solutions regarding the problems examined. In this connection, the Group was also charged with analysing the experimental data collected from recent earthquakes, with a view to determining how they can be applied to the improvement of the seismic safety assessments and the antiseismic design of nuclear installations.

From this it is evident that there is co-ordination existing with the second initiative taken by CSNI at the same
time. This was the decision of co-sponsoring and organising in collaboration with the Italian nuclear authorities a Specialist Meeting specifically focussed on the review of the very numerous data of a geological, geophysical and structural nature collected during the Friuli earthquake by scientific teams coming from several countries. This is perhaps a unique opportunity for improving the data base for the antiseismic design, because the Friuli earthquake, due also to the exceptional duration of its manifestations, is now probably the most instrumented and recorded earthquake in the world.

The goal of the Specialist Meeting is therefore that of interpreting and discussing the experience of Friuli with a view to drawing from its data all the lessons which may be applied to developing more satisfactory methods for the evaluation of the seismic risk and the connected determination of the design basis reference earthquakes for nuclear plants.

These are, in fact, the basic tasks of the Expert Group, which is presently concentrating its attention on four fundamental problem areas, namely:

- the definition and description of the source terms, including the examination of the applicability and the relative merits of the probabilistic and deterministic approaches to the seismic risk evaluation;

- the determination of the terms of propagation of the seismic disturbance, including the problems of extrapolating seismic wave propagation laws from country to country and from weak to strong ground motions;

- the determination of the relative effects on structures due to the different types of seismic waves and the available methods for describing the physical parameters of ground motion in terms appropriate for the antiseismic design of structures;

- the present state of practical experience achieved through the study and recording of actual earthquakes and their effects.

The final goal of the two co-ordinated actions I have briefly described would be that of attaining in this field a better level of international co-operation through the adoption by CSNI of consensus statements about the problems examined and the solutions suggested. Therefore, CSNI expects that your conclusions from this meeting will point out explicitly which part of the Friuli experience might be susceptible to being transferred, or of giving useful pay-off, to the field of nuclear safety and the antiseismic design of nuclear plants, and what further practical actions of international co-operation in this field you recommend for implementation by CSNI and NEA.

Before making room for the experts, I should like to thank the Italian Comitato Nazionale Energia Nucleare and the
Italian Ente Nazionale Energia Elettrica for having so kindly offered to host this meeting. Particular thanks are also due to Dr. Forti and her colleagues who have worked so hard to lay the necessary foundation for a successful meeting.

I wish you success in your deliberations.
INTRODUCTORY SESSION: THE 1976 FRIULI EARTHQUAKE
PRESENTATION OF THE FRIULI EARTHQUAKE
P. Giuliani, CNEN

Good morning, ladies and gentlemen. My name is Pietro Giuliani, I work in CNEN, Safety Division. I have been given the task of making a brief outline of the Friuli earthquake of 1976.

The 1976 Friuli seismic period began, at least in its most dramatic form, on the evening of the sixth of May 1976 at 19h59m03s GMT, with a shock of magnitude 4.5 RMP. This shock was the only foreshock. Just about one minute later, at 20h00m12s GMT, it was followed by the main shock, the magnitude of which has been evaluated by different observers to be between 6.2 and 6.5. The areas stricken by the earthquake is located in the north-eastern part of Italy, close to the border with Austria and Yugoslavia, between the Po valley and the Giulie and Carniche Prealps. I will show you a slide. In this slide the epicentral area has been drawn schematically and it is up there, in the right hand corner of the picture, and intensities are in the MCS scale.

The epicenter of the shock is located near Gemona, as you can see. Gemona has been one of the most damaged communities during this earthquake, both in terms of loss of life and in terms of damage to buildings and public works. The focus of the earthquake has been evaluated at different depths by different observers, but I believe, however, that this particular topic will be discussed at some length during this meeting. We have another slide, now. This slide has been taken from Karnik's publication, as you can see under it. In this slide you can see two lines of equal intensity in the MKS scale. In the epicentral area, the maximum intensity has been felt in very small areas. The earthquake has been felt up to distances of about 700 km in a north-eastern direction. Following the main shock, an extensive and diffused seismic activity, which has interested an area of more than 600 km\(^2\), has characterized this earthquake. At first there has been a very large number of shocks, both of comparatively high and low magnitudes; the frequency and magnitude of shocks have decreased with time. Even so, every now and then, there have been sudden bursts of stronger activity.

Then, a few months after the first shocks in May, in the first days of September 1976, a new and strong seismic phase began. This phase has its maximum shock on September 15th 1976, and the magnitudes were respectively 5.9 and 6.1 for the two main shocks. Last September, just last month, in September 1977, there has been a new shock, of magnitude 5.1.

It is a bit difficult to tell the total number of shocks, during this seismic event; there have been more than 1000 shocks of magnitude higher than 2.5, while the number of shocks of magnitude higher than 4.5 has been over 50.
As Dr. Ilari said before, and Dr. Mittempergher, this seismic event has been one of the most instrumented ones in recent times.

Now, let's see what was the situation of seismic instrumentation. At the beginning of May 1976, that is, just before the main shocks, within a radius of 100 km from the epicentral area, the following seismic instrumentation was operational.

There were six seismographic stations of ENEL, located at six dam sites. Then there were three clinographs, which were located at ENEL dam sites. Then we had five strong-motion accelerographs of the ENEL network and then, within the same 100 km radius, there was the Trieste Experimental Geophysical Laboratory.

Beyond this radius of 100 km, there is the seismic network of the Istituto Nazionale di Geofisica, the national accelerometric network of ENEL and CNEN instrumentation.

Now we have a slide on this. In this slide it is possible to see the accelerometric stations which were in the area of the earthquake and it is possible to see, the red dots are the stations which were already in the area before the earthquake, and you can see those circles, the blue ones and the yellow ones which are stations which were installed just after the first shock, both by ENEL and by CNEN. I believe you can read from your positions the legenda on the right hand corner.

The next slide shows the extent of the accelerometric network of ENEL over the whole of the Italian territory. This network has been in operation for quite some time now and a number of these stations were triggered by the Friuli earthquake. The Friuli area, for those who are not familiar with Italy is on top of the slide.

Just after the first shocks in May 1976, several Italian and foreign agencies, both public and private, beyond CNEN and ENEL, many of these agencies are attending this meeting, have installed in the earthquake area other instrumentation in addition to the one which has been shown on the slides.

The purpose of this additional instrumentation has been the collection of data on the various physical parameters of the earthquake. Of course, this has brought forward quite a lot of research in the field of seismology, geophysics, soil mechanics and seismic engineering.

This earthquake has been quite heavy in its toll of life and property. The casualties have been about 1000 deaths and more than 5000 wounded. A very large number of buildings, both public and private and public works have been destroyed. In monetary terms, the economic loss has been evaluated to be something like 6000 billion lire, which in US $ would be something like 8 billion US $, $8 \times 10^9$.

Now we have a new reel film which has been adapted, actually cut, from a new reel which was taken, shot, by the Italian Television Network just after the first shock in May 1976.
THE BROAD GEODYNAMICAL FRAME OF FRIULIAN SEISMICITY

L. Ogniben
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According to the plate tectonics model, a compressive deformation takes place along the entire Alpine range, which happens to be in the so-called "Mediterranean phase" of DEWEY (1969), that is, the collision phase between two previously independent Pacific-type orogenic belts. Two sectors of the Alpine range which have been fairly well illustrated in the geological literature under this respect are the Zagros Mountains and the Himalayan chain. The Friuli seems to be another of such particular compression sectors, with an important difference: while in the Zagros and Himalaya the southern plate undergoes the northern one, in East Alps on the contrary the southern plate overruns the northern one.

The problem will be considered here as an attempt to fit the Friulian seismicity in a broad geodynamical frame, for an easier understanding by people from other regions.

In the Alps the marginal chains of two different plates, Eurasia and Africa, are laid one upon the other. This comes out from the evidence of two broad seams of ophiolites, the Pennidic and the lower-austridic ones. These could not be recorded at the surface if in the folding process they were not laid upon their own continental margins, which thus became characterized and recognizable.

These continental margins had to be originally distinct from each other and converging westwards where they united at Gibraltar, as it seems well witnessed by geological evidence. Moreover, the well known Atlantic magnetic lineations lead us to calculate a rotation of Africa towards Eurasia such as to shift the Italian region northwards for something like 2500 km from the beginning of Atlantic spreading 120 MY ago, with an average velocity of 2.4 cm/y according to LE PICHON (1968) or 2 cm/y after the figures (Fig. 1) of MCKENZIE (1972). Attempts to synthesize the known geological evidence gave rise to some hypotheses wholly different from this one. They are, however, all more or less bound to a paleogeographical way
of thinking older than the knowledge of ocean floor spreading, and are therefore controlled by a view of Alps as one from the origin unique orogenic belt, what does not consist with the factual evidence of Eurasia converging with African, Arabian and Indian plates.

An extremely rough dating of Alpine orogenic events can be attempted starting from the fact that related stratigraphic sequences begin with Permian levels and end some 50 MY ago with the Paleocene flysches, both in the Pennides as in the Austrides, and in Pratigau also Lower Eocene ones. Therefore, the folding phases proper in both chains are around the 55-38 MY of Eocene time, following the "Early Alpine metamorphic phase" of COMPAGNONI et al (1977). The fact that Lower Austridic ophiolites overlie Mesozoic, Paleozoic and Crystalline sequences informs us that they have been thrown on the Austridic continental margin by a southwards verging folding phase, prior to the northwards verging collision phase between the two chains.

The "Lepontine metamorphic phase" with its peak some 38 MY ago seems to be likely to date the deformation maximum of the Alps, which should be that of the Austrides overriding the Pennides. The southern-alpine Molasse also begins after that moment, what seems to date the uplift of the Austrides when overriding the Pennides.

We face now the problem of evaluating the deformation of the new double Alpine chain issued from the Pennides-Austrides collision. Without expecting too much accuracy from such calculations, we may refer to CADISCH (1953), who estimates the Swiss Alps narrowing as much as from the original 630 km to the present 150 km. Adding the Southern Alps we may roughly expect a total narrowing from former some 750 km to the present 200-250 km. In this order of estimate are comprised the early heaping up of Pennide nappes northwards and of some Lower Austride nappes southwards, the subsequent Austride overlap on the Pennides, and the consequent northwards compression and deformation of the whole.

At an average 2 cm/y velocity a time span of 25 MY would have been necessary. If we take into account a drift slackening during the compression
phase subsequent to collision, and also the lateral spreadings due to uplift, we can reach the 38 MY of the beginning Oligocene and of the Lepontine phase, and may be still more backwards.

If the oceanic magnetic lineations are considered, an original distance between the Austride continental margin and the Pennide one must be accepted, equal to total convergence between Africa and Eurasia, minus the amount of convergence due to deformation after the collision. That is something like 2000 km. Of this ocean the Tyrrenhian-West Mediterranean window seems to be left, which is in way of closing through northwards crushing of the double Apenninic bend from Piedmont to Sicily. This in turn pushes eastwards Calabria, northern Greece and northern Turkey, and the Friulian salient is pushed northwards. As we see, the latter seismic area is actually connected with other well known Mediterranean seismic areas in an unique broad frame.

This premise was necessary to be able to state that after the Alpine collision we are bound to a realm of purely crustal deformation within depths of some tens kilometers. It is a matter of intraplate tectonics, no longer a tectonics of plates comprising a heavy deep lithosphere. This one seems to remain below the light crust, without entering in any known manner in the deformation of the latter, apart from the early emplaced ophiolites and from some rare controversial instances as that of the deep seismicity of Calabria. In order to properly speak in general of Mediterranean seismotectonics and particularly of Friulian one, it appears fit to point out that if the term subduction means the sinking of lithospheric plates down to maximal depths of 700 km into the mantle, it is confusing to use the same term for phenomena within the crust, restricted to maximal depths of 70 km, and much less in Friuli. In such cases we will more correctly speak of underriding or overriding, or of underthrusts or overthrusts. We will speak of plate boundaries only where this will be confirmed by geological records, while in the cases of seismicity restricted to the crust we will generally have to do with boundaries of intraplate crustal slabs.
The choice of the terms "ride" or "thrust" depends on physical concepts, that is on thinking that there are body forces involved or else boundary forces. First ones could be ascribed to drifting inertia, but also boundary forces could be held responsible for the same deformation and shortening phenomena by collision, since boundary forces at the margins of continental crust would be bound not to the small strength of the latter, but to its unsinkability into the mantle, that is to its weight.

In the Friulian salient these forces seem in any case to give rise to the northwards stress of the Venetian-Friulian-Julian crust against the thickened Alpine crustal belt due to Pennide-Austride foldings, then to their overlapping, then to the consequent isostatical uplift the dike against this thrust is marked by the Alpine-Southalpine boundary, or better by its stretch called Gail line (Fig. 2). To this boundary different meanings have been attached, but the likeliest is that it represents a major overthrust, presently set upright by the uplift of the belt marked by the Tauern window.

The push against this obstacle appears to give rise to fault structures, which are nothing but shear planes determined by the disposition of the principal stress axes. The axis of major principal stress will be parallel to the vector of the earthquake-producing forces, while the intermediate and minor principal stresses will be bound to weight and confinement of the involved crust. From the ensemble of the fault planes we can therefore get an idea of the most important and lasting causes of the seismicity.

South of the Gail line we know in Friuli somewhat different fault systems West and East of the Tolmezzo meridian, but to a closer consideration they appear mechanically consistent with each other (Fig. 3). Eastwards we find a system of EW directed inverse faults, which are symmetrically overthrust northwards at Nord, southwards at South. SELLI (1963) describes them as bilaterally underriding a median plate. The same picture repeats itself West of the Tolmezzo meridian, but with a strong predominance of the southwards overthrust structures. This different behaviour in the two areas is ascribed by SELLI (1963) and by MARTINIS (1971) to different lithological composition
of the concerned crust, due to prevailing plastic Triassic rocks westwards and to prevailing rigid Triassic carbonate rocks eastwards, and also to a greater tectonical gradient W of the Tolmezzo meridian due to subsidence in southern Friuli (Fig. 4).

The picture is completed first by the prevailing NE-SW directions of geological structures towards the West side of the Friulian mountains, and by the NW-SE directions towards the East side and the Triest Karst. In this way a Friulian salient of northwards oriented compressive strain is outlined, which apparently is bound to the major principal stress axis. Secondly, a noteworthy cluster of NNE-SSW or NE-SW directed faults appears to be concentrated in the region of lithological break in the Triassic sequence near Osoppo and Tolmezzo, that is in the earthquake area. The faults are vertical or nearly so, and most of them probably strike-slip faults.

The most important EW directed overthrust structures with southward vergency are considered by the authors to be due to gravitative flow of the sedimentary cover as a result of quick and strong uplift of the northern Friulian Alps since Late Cenozoic up to Recent times. This is undoubtely true for the unconfined superficial terminal parts of the overthrusts, where plenty of differential sinkings have been reported also for the 1976 earthquake. It seems less so for the overthrust surfaces sinking in depth northwards, which are not known to rise into view anywhere more northwards, as a gravitatively sliding slab would do.

Advancing something of what will probably be dealt with in great detail in this meeting, we can take notice that for the surroundings of the 1976 earthquake area the seismological evidence of the past mostly reports NE-SW oriented sinistral strike-slip focal mechanisms (CAGNETTI, PASQUALE & POLINARI, 1976), while for the 1976-5-6 major shock a thrust-type mechanisms reported (CONSOLE, 1976; MUELLER, 1977) with the Adriatic block underthrust about northwards with 348° azimuth and 13° dip. The focal depths of the numerous shocks from 1976-5-6 to 1976-6-11 are given by CNEN-ENEL (1976)
from 30 to 1 km, as a good evidence of involvement of the sole crust. The epicenters are fairly well located along the bundle of overthrusts at the S margin of the Friulian mountains.

The seismological records appear therefore to be consistent with the tectonical structures in outlining an axis of major principal stress in NS direction, both for the strike-slip as for the thrust mechanisms. For the former or the latter to take place it depends on the positions of the intermediate and minor principal stress axes. For a vertical intermediate principal axis the focal mechanism and the resulting fault will be of strike-slip type due to vertical shear planes. This seems to be the normal case, the crust weight being normally greater than its cohesion (Fig. 5 A). But if the vertical principal stress will be lessened by isostatical uplift reaction, or if the lateral principal stress will be enhanced by confinement, the resulting shear planes will be inclined, with a focal mechanism and an ensuing fault of thrust type (Fig. 5 B). Gravitative sliding phenomena will also take place, but in the unconfined superficial regions of the overthrust slab. The last case (Fig. 5 C) will be that of horizontal minor principal stress axis due to tangential stretching of the crust, with the crust weight acting as vertical major principal stress. The resulting shear planes will be inclined, with a focal mechanism and an ensuing fault of the normal dip-slip type.
REFERENCES


FIGURE CAPTIONS

Fig. 1 - The relative motion between Africa, Arabia and Eurasia obtained from Atlantic magnetic lineations, as represented in MCKENZIE's (1972) Fig. 4.

Fig. 2 - The sense of stress in Venetian-Friulian-Julian Southern Alps against the Gail Line and the Alps proper.

Fig. 3 - Fault systems outcropping in Friuli.

Fig. 4 - Overthrusts as shear planes in Friulian Alps.

Fig. 5 - Faults as shear planes in stress ellipsoids. A = strike-slip faults; B = thrust faults; C = normal or dip-slip faults; $\sigma_1$ = major principal stress; $\sigma_2$ = intermediate principal stress; $\sigma_3$ = minor principal stress.
A

$G_1 = \text{push by continental drift}$

$G_2 = \text{crustal weight}$

$G_3 = \text{crustal cohesion}$

B

$G_1 = \text{push by continental drift}$

$G_2 = \text{crustal cohesion plus lateral confinement}$

$G_3 = \text{crust weight}$

C

$G_1 = \text{crust weight}$

$G_2 = \text{crustal cohesion}$

$G_3 = \text{tensile stress by crust stretching}$

FIG. 5
SESSION I.a - GEOTECTONIC, GEOPHYSICAL AND SEISMOLOGICAL ASPECTS:
GEOTECTONICS

Chairman: L.S. Cluff
Scientific Secretary: M.J. Berry
Invited paper

LE SEISME DU FRIOUL (Italie, 6 mai 1976)
DANS SON CONTEXTE SISMOTECTONIQUE

C. Weber et P. Courtot
B.R.G.M.
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ABSTRACT - A better understanding of the mechanism of the May 6 Friuli earthquake can now be developed by considering the coherence of the elements of the entire set of available data. The data include: (1) structural criteria, (2) interpretation of the satellite images, (3) recent tectonics, (4) historical seismicity, (5) macroseismic observations, (6) study of the aftershocks of the two main quakes, (7) fault-plane solutions. A consistent set of conclusions from these data allows us to interpret the Friuli earthquakes in relation to a crustal compression of approximately NW-SE direction, which remobilizes pre-existing faults. They are of two types: (i) left lateral strike slip, clearly identified on Landsat images and observed on ground along the right bank of the Tagliamento river, (ii) low angle thrusts, where are located a great number of aftershocks. The complexity of the faulting explains the difficulty in interpreting the different fault-plane solutions which have been computed. A new focal mechanism is given for the main shock. It shows left handed strike slip which could be related to the Tagliamento and Buia fault system. Fault-plane solutions for the aftershocks mostly indicate thrust fault mechanisms.

RESUME - Le mécanisme du séisme du Frioul peut actuellement faire l'objet d'une tentative de compréhension par une recherche des éléments de cohérence dans l'ensemble des données disponibles. Elles comprennent: (1) le cadre structural, (2) l'interprétation des images-satellite, (3) la néotectonique, (4) la sismicité historique, (5) les observations macrosismiques, (6) l'étude des répliques des deux chocs principaux, (7) les solutions de plan de faille. Un faisceau convergent d'arguments permet de considérer que les séismes du Frioul sont liés à une compression générale de la croûte, sensiblement NW-SE, qui a remobilisé des accidents pré-existants. Ces derniers sont de deux types: (i) déplacements latéraux sénestres orientés N 5° à N 50°, bien visibles sur images-satellite et observés sur le terrain sur la rive droite du Tagliamento, (ii) failles de chevauchement E-W, sur lesquelles se trouve localisée la majorité des répliques. Cette complexité explique les difficultés d'interprétation des différentes solutions focales calculées. Un nouveau mécanisme au foyer est calculé ; il montre pour le choc principal un déplacement latéral sénestre qui pourrait être rapporté au système de failles Tagliamento et Buia. Les répliques donnent par contre pour la plupart des mécanismes de chevauchement.
D'importants travaux de terrain dans la province italienne du Frioul ont suivi le séisme catastrophique du 6 mai 1976 (M = 6,4). Les très nombreuses répliques ont pu être enregistrées avec une précision tout-à-fait remarquable. Des mécanismes au foyer ont été calculés, souvent très différents les uns des autres. Bien qu'une très faible partie de ces études ait fait à ce jour l'objet de publications, il paraît essentiel de tenter une synthèse sismotectonique, à partir des travaux disponibles (1). Il est possible actuellement de préciser les hypothèses sur l'origine du tremblement de terre, que VOGT J. et WEBER C. (1) avaient émises immédiatement après le séisme, à partir de quelques observations de terrain et de l'interprétation des images-satellite. L'approche sismotectonique consiste à examiner individuellement, dans un premier temps, les données des divers volets (cadre structural, images-satellite, néotectonique, sismicité historique, observations macroisismiques, étude des répliques, mécanismes focaux (2)), et d'en retirer ensuite les éléments de cohérence qui permettent d'appuyer l'interprétation.

**LE CADRE STRUCTURAL**

Dans la partie centrale du Frioul, le Tagliamento sépare les Alpes carniques à l'Ouest des Alpes juliennes à l'Est. Dans les premières, dominent les faciès pélagiques avec, pour les termes plastiques, une épaisseur évaluée à 4 000 m, alors que dans les Alpes juliennes les faciès récifaux sont plus abondants. Ces dissemblances induisent un comportement tectonique différent.

L'épicentre du séisme du 6 mai (46° 17' N et 13° 07' E) se situe dans les préalpes juliennes occidentales. Leurs matériaux mésozoïques, dolomitiques ou calcaires, forment une série d'écailles tectoniques complexes, séparées par des contacts anormaux à pendage nord, souvent sub-horizontal. Les écaillres chevauchantes correspondent fréquemment aux reliefs les plus importants. Elles reposent sur des terrains autochtones qui affleurent principalement au Sud d'une ligne Forgaria-Bergogna, et sont surtout constitués de flyshs écocènes et de grès et conglomerats miocènes. On trouve plus au Sud la grande dépression molassique d'Udine, contenant une série miocène épaissie de 1 500 m environ.

Deux phases de plissements alpins ont été identifiées. La première est datée du début du Miocène : les chevauchements principaux sont post-burdigaliens (- 15 MA), peut-être même fini-miocènes (- 7 MA) ; à l'Ouest du Tagliamento, en certains points (basse vallée de l'Arzino) le "Pontien" est plissé à 45° (COUSIN M. (2)). Les chevauchements sont recoupés par des failles transversales, d'orientation dominante NE-SW.

(1) Les auteurs qui ont bien voulu nous communiquer un pré-tirage de leur article sont tout spécialement remerciés.

(2) Les données de géophysique de prospection n'ont pas été accessibles.
IMAGES-SATELLITE

La fracturation récente, postérieure à la mise en place des nappes, apparaît clairement sur les images-satellite (par exemple, les scènes ERTS du 6 août 1973 et du 24 février 1975). Les accidents qui affectent la zone pré-alpine se poursuivaient dans la plaine plio-quaternaire de Vénétie. Deux directions de fracturation dominent, l'une N 5° à N 50°, l'autre N 120° à N 160°. La première est illustrée principalement par une double cassure, Tolmezzo-Conegliano et Pioverno-S. Dona di Piave ; elle représenterait un jeu latéral senestre particulièrement net le long du Tagliamento en aval du confluent du Fella. La seconde correspond d'une part à la limite sud des flyschs de la fosse julienne, selon une ligne Tarcento-Cividale et d'autre part à des accidents parallèles à la côte nord-orientale du Golfe de Trieste. Il peut s'agir de failles inverses présentant probablement un déplacement latéral dextre. Un tel schéma laisse penser que les contraintes tectoniques récentes se manifestent par une compression orientée N-S à NW-SE.

NÉOTECTONIQUE

Les informations publiées au sujet d'indices de mouvements néotectoniques en Frioul sont rares. Lors de la réunion d'Udine (4-5 décembre 1976), ZANFERRARI A. a présenté une étude de la fracturation des formations villafrianchiennes de la rive droite du Tagliamento, entre Tolmezzo et Forcaria, en montrant l'existence d'un double réseau de fracturation, de directions principales B 30° et N 150°. Des observations fines, il conclut à des mouvements horizontaux dominants.

SISMICITÉ HISTORIQUE

Les Alpes carniques et juliennes présentent une sismicité élevée. Le tremblement de terre dit de Villach, près de la frontière autrichienne, en 1348, est l'un des plus considérables dont l'Europe alpine ait jamais eu à souffrir ; il aurait fait des dizaines de milliers de victimes d'après MONTESSUS de BALLORE. Une intensité X (échelle MSK) lui a été attribuée. Plus près de nous, les séismes de Verzeichn (près de Tolmezzo) en 1928 et de Causiglio (au SE de Belluno) en 1936 auraient atteint une intensité épicentrale de IX (magnitude respective 5,8 et 5,6). Le catalogue des séismes (FELIZIANI P. et MARCELL L. [3]), localisés en Italie Nord-orientale depuis le début de notre ère, recense 266 secousses principales ; l'énergie sismique libérée par siècle, telle que ces auteurs l'ont calculée, est relativement constante. La figure 1 reprend ces données. Il se trouve que la région de Gemona a déjà connu un séisme important, d'intensité supposée IX, le 26 mars 1511, qui a provoqué l'effondrement de l'église de cette ville, des dégâts importants à Faedis, Artena et plusieurs glissements de terrain [4][5]. Son aire macrosismique est très étendue ; à Tolmezzo il fut ressenti avec une intensité VIII. Les répliques ont duré près d'une année, jusqu'en février 1512.

FELIZIANI P. et MARCELL L. [3] ont donné par ailleurs de nombreuses cartes d'isoseïstes pour les tremblements de terre du XXème siècle. On ne peut manquer d'être frappé par le fait que la vallée du Tagliamento apparaît fréquemment avec des intensités plus élevées que dans les vallées
confluentes. Si un effet lithologique est possible, il ne peut expliquer à lui seul le tracé des isoéistètes du séisme de Moggio-Udinese (25 avril 1939) (fig. 2). Un effet tectonique paraît plus probable.

LES OBSERVATIONS MACROSISMIIQUES


L'observation des cassures dans le sol, formées lors du séisme, n'apporte pas d'information structurale décisive au sujet du type de mouvement de faille. En effet, elles affectent, pour la plupart, les formations récentes hétérogènes de la vallée du Tagliamento ; nombre d'entre elles peuvent être expliquées par des tassements différentiels. De la cartographie réalisée par MARTINIS B. [9], on peut retenir deux directions dominantes : N-S et E-W à NW-SE. Une étude systématique des traces superficielles de la déformation crustale (TOKUYAMA A. [10]) signale quelques indices d'un coulis-sage latéral gauche. L'ensemble de ses observations permet de déterminer un axe de compression maximum orienté NW-SE.

L'ÉTUDE DES RÉPLIQUES

La répartition spatio-temporelle des répliques du séisme du 6 mai est parfaitement connue grâce aux résultats du réseau de sismographes installé dans le Frioul par l'Institut de Physique du Globe de Strasbourg, 80 h seulement après le choc principal (HOANG P. et al. [11] ; FINETTI I. et al. [12]). Plusieurs milliers de séismes ont été enregistrés (3 700 du 10 au 14 mai). La plupart d'entre eux sont localisés avec une précision de ± 250 m, profondeur comprise.

Les répliques du tremblement de terre du 6 mai sont principalement réparties dans une ellipse allongée E-W, centrée sur Gemona et couvrant une superficie d'environ 200 km². Les répliques suivant le choc du 15 septembre (M = 5,9) se trouvent en majorité dans une ellipse d'environ 270 km², décalée de 8 km vers le Nord par rapport à la précédente. On observe également une migration des profondeurs : 2,5 à 7 km pour les répliques de mai, 4,5 à 10 et 18 km en septembre. Les auteurs précités montrent à l'Est du Tagliamento une bonne corrélation entre la répartition des hypocentres et celle des failles inverses reconnues par sismique-réflexion. Les répliques de mai peuvent correspondre à des plans de faille de très faible pendage nord, celles de septembre à des plans inclinés à environ 45° vers le Nord.
Les mécanismes focaux calculés pour les répliques varient très nettement d'ouest en Est, et permettent de distinguer quatre zones [12] :

- région du lac de Cavazzo : failles à déplacement latéral uniquement ;
- région de Peonis : failles à déplacement latéral et chevauchement ;
- région de Gemona : chevauchements de pendance 30° N environ ;
- région Est de Venzone : chevauchements.

Ces mécanismes montrent très clairement la complexité des phénomènes tectoniques en jeu et la difficulté de ramener à une origine simple les secousses sismiques ressenties dans le Frioul.

LES SOLUTIONS DU PLAN DE FAILLE DU CHOC PRINCIPAL

Le calcul d'un mécanisme au foyer apporte des éléments nécessaires (mais non pas suffisants) pour connaître la répartition régionale des contraintes. Encore faut-il que les solutions calculées soient dépourvues d'ambiguïté, ce qui est rarement le cas [13][14]. MÜLLER G. [15] a publié une solution bien définie grâce à l'étude de la polarisation des ondes S pour des stations des États-Unis et du Japon. Elle correspond à un plan de chevauchement subhorizontal (plongement de 13° vers le N-NW).

Il nous a paru utile de reprendre le calcul du mécanisme du choc principal du 6 mai à partir de données disponibles à la mi-1977, soit 54 stations des réseaux W.W.S.S.N. et canadien (dépouillées à partir des microfilms), 5 stations du L.D.G.-C.E.A. et 6 stations italiennes. La détermination des plans nodaux a été réalisée en utilisant le programme par méthode statistique de WICKENS A.J. et HODGSON J.H. [16][17] modifié afin de prendre en compte les données de stations dont la distance épicentrale est inférieure à 20° (modèle de croute d'épaisseur 20 km et de vitesse 6,1 km/s surmontant un milieu de vitesse 8,2 km/s). Afin de conserver des angles d'émergence au foyer compris entre 0 et 90°, les angles et les azimuts des ondes Pg ont été augmentés de 180°, ce qui a pour effet de représenter la donnée dans son quadrant opposé de même signe.

La solution obtenue (figure 3 et tableau annexe) montre un groupement en quadrants acceptable, dans la mesure où il ne présente que sept données incompatibles (projection de WULFF, demi sphère inférieure). Sa qualité est bonne pour le plan C, choisi comme plan auxiliaire ; la densité des données au voisinage et de part et d'autre de ce plan est satisfaisante. Le plan A, parfaitement compatible avec les données géologiques, a été choisi comme plan de glissement. Bien qu'il n'offre pas un degré de certitude comparable, il représente une solution cohérente avec les données de polarisation des ondes S calculées par MÜLLER G.. Sa position est déterminée essentiellement par les données des stations proches françaises (ondes Pn). Le mécanisme focal calculé est donc interprété comme un déplacement latéral senestre, suivant un plan de faille sensiblement Nord-Sud. Les axes de pression maximum, subhorizontaux, ont une orientation SE-NW.
CONCLUSION

La plupart des interprétations sismotectoniques du tremblement de terre du Frioul (en particulier FINETTI et al. [12]) mettent l'accent sur le rejeu en compression des chevauchements péri-adriatiques, et relient directement l'activité des répliques à celle du choc principal. Dans ce cadre, les nombreuses indications de déplacements latéraux sont difficilement explicables.

L'étude et la confrontation de la plus grande partie des données sismotectoniques à notre disposition conduisent à envisager un mécanisme complexe ; en particulier l'activité des répliques peut être différente de celle de l'événement principal. Un tel fait n'est pas rare pour les séismes supracrustaux ; tel est le cas, par exemple, de San Fernando [18] ou de Kern County [19] en Californie. Il est vraisemblable que le choc principal corresponde au rejeu de failles à déplacement latéral senestre du système Tolmezzo-Conegliano marqué dans la région de Gemona par les failles subméridiennes du lac de Cavazzo, du Tagliamento moyen et de Buia. Cette dernière aurait été la plus active ; son azimut est approximativement celui calculé dans la solution focale proposée (fig. 3). Par contre, les répliques se situeront préférentiellement sur les failles inverses de chevauchement orientées Est-Ouest, dont l'allure en profondeur est connue par sismique-reflexion. L'activité des répliques s'est d'ailleurs déplacée en 1976 vers le Nord, en s'approfondissant.

L'analyse statistique des secousses du Frioul enregistrées par le réseau du L.D.G.-C.E.A. [20] montre que la relation fréquence-magnitude est nettement différente pour les faibles secousses (M < 4,5) et pour les quatre chocs de magnitude supérieure à 5,5. Pour les premiers, le coefficient b est de 1,38, pour les seconds de 0,89. Ainsi il se confirmerait que les contraintes sont relachées de façon bien différente par les répliques et par les forts séismes.

La complexité des phénomènes mis en jeu par ces mécanismes ne peut surprendre, en raison de la grande variété des tectoniques superposées dans les Alpes juliennes. La direction de compression maximum calculée par notre solution focale, direction d'ailleurs sensiblement identique à celle trouvée par MÜLLER G. [15], correspond à un état de contrainte tout-à-fait compatible avec les données géologiques et sismologiques relatives à la Méditerranée occidentale. Ces données peuvent être interprétées en terme de tectonique de plaques "classique" (MAC KENZIE D. [21]) ou de collision continentale faisant appel à un poinçonnement oblique et progressif de l'Europe par l'Afrique (TAPPONIER P. [22]).
REFERENCES


FIGURES

Figure 1 - ESQUISSE SISMOTECTONIQUE DU FRIOUЛ.

- Cadre structural, d'après SELLI R. [23], modifié [2], [24], [25], [26].
  1 - chevauchement,
  2 - faille principale,
  3 - faille supposée et/ou faille récente d'après imagesatellite.

- Séisme du 6 mai 1976
  4 - isoséistes, d'après [7] et [8],
  5 - aire de localisation préférentielle des répliques du mois de mai, d'après [12]. Nota : en raison de la géométrie du réseau de sismographes, cette aire peut être plus étendue vers l'Est.
  6 - aire de localisation préférentielle des répliques du mois de septembre 1976 [12].

- Sismicité historique, principalement d'après [3], intensités MSK.
  7 - épicentre de localisation incertaine.

Figure 2 - ISOSÉISTES DU SÉISME DE MOGGIO-UDINESE, 1939
extrait de [3].

Figure 3 - MÉCANISME AU FOYER DU SÉISME PRINCIPAL DU 6 MAI 1976
(se reporter au tableau annexe).

- Solution des plans nodaux

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- Figure 1 -
MOGGIO UDINESE - BORDANO - 25 aprile 1939 - GRADO VI

SCALA CHILOMETRICA

- Figure 2 -
### TABLEAU ANNEXE

Mécanisme local du séisme du Frioul

6 mai 1976 à 20 h 00 am 12 sec

- Liste des stations utilisées

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GEOLOGICAL AND MORPHOLOGICAL PHENOMENA CAUSED BY HIGH SEISMICITY
AS A NATURAL SOURCE OF INFORMATION ON RECENT SEISMICITY

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**) Laboratorio di Geologia Applicata alla Pianificazione Viaria ed all'Uso del Sottosuolo del C.N.R., Padova (Italy)

ABSTRACT

It is well known that high seismicity leads to geological and morphological phenomena in seismical areas. The parameters of some of these were examined: (a) rockfalls; (b) earthquake cracks, "surface faulting", sedimentary dikes; (c) changes in the hydrographic network.

A nation-wide census of phenomena of the kind described is recommended, as a means of gathering supplementary information on the past seismicity of high degree. Their recognition is of particular interest in regions considered as free from earthquakes, but with a recent history of intense geodynamic activity.

RESUME

Il a été constaté que des phénomènes géologiques et géomorphologiques de genre particulier auraient une liaison avec la sismicité de haut degré. Les suivants ont été distingués: (a) éboulis; (b) crevasses, "surface faulting" et filons sédimentaires; (c) variations du réseau idrographique.

Leur recensement compléterait les données historiques et instrumentales à disposition, en ce qui concerne l'espace de temp couvert en ce genre d'enquête. Leur identification, particulièrement en régions actuellement retenues non sismiques pour le manque de connaissance d'une sismicité historique, pourrait donner un apport valable pour l'évaluation du risque sismique.
1. In Italy, the free exchange of views between seismologists, geologists and geophysicists is of recent origin. In discussion of this kind, the geologist contributes his experience with respect to the identification and characterisation of seismogenetic structures, and the evaluation of geological parameters that interfere with the propagation of seismic waves.

The more one examines the complex problems associated with the assessment of seismic risk, the more convinced one becomes that both geology and geomorphology can aid in overcoming what is perhaps one of the weakest points in the various methods employed for such assessment, namely the gaining the knowledge of the seismic activity associated with a given region in the past. It is generally admitted that the historical and instrumental data samples with which this several methods are forced to operate are too short to be of statistical significance. Irrespective of the soundness that one may or may not be inclined to attribute to the application of probability analysis to data on earthquakes, there can be no doubt that the past seismicity of an area is the main objective finding on which one can attempt to rely in assessing the seismic risk.

The primary aim, therefore, is to acquire as much knowledge as possible of the distribution of seismic phenomena for as back as one can in the past. It is obvious that the evidence of seismic activity offered by geology and geomorphology will be more satisfactory than historical and instrumental data from these standpoints, especially with respect to the more important aspect of the matter, namely the chronological picture.

2. That severe earthquakes \( (M > 6.5) \) are responsible for a series of both geological and geomorphological phenomena is well known. If one could make an assessment of every phenomenon of this kind that can be recognized in a given area, the sample of high degree seismicity, which, after all, is that which is of greater concern from the social and economic angles, would certainly cover a much wider period than that offered by the historical record.

The present paper deals with a series of such phenomena, in the hope that in the future their more precise definition will lead to their easier and more certain identification. Indeed, their collection and the eventual establishment of parameters therefrom could, perhaps, result in the elaboration of a method for evaluating seismic risk that would both supplement and act as a check on the "pattern recognition" of geological and geomorphological phenomena method devised by Gelfand & al. [1].

In the case of geological and geomorphological phenomena associated with seismic activity, the earthquake is not necessarily the most important contributor to the phenomena themselves, though it certainly makes them typical. This sort of "style" is apparent in a series of features that distinguish such phenomena from those more generically associated with neotectonics.
In the final analysis, all this phenomena lead as the result of seismic vibration to ground rupture of which they are the direct or indirect evidence.

Rupture of this kind may be:

(a) **earthquake cracks**, being the result of distension;

(b) **surface faulting**, which can be the result either of compression or of distension.

Which type of rupture occurs will also depend upon geological and morphological factors. E.g., it will be evident that different consequences may be expected when a steep slope with massive rocks as opposed to an alluvial plain is involved.

We will now describe some different types of rupture observed after the Friuli earthquake (3.1.1., 3.2.1., 3.3.1.). In addition evidence of similar manifestations of seismic activity in the past, both in Friuli (3.1.2., 3.2.2., 3.3.2.) and elsewhere in Italy (3.1.3., 3.2.3., 3.3.3.), will be presented.

3.1. **Rockfalls** offer an indirect sign of the rupture of the topographical surface confined to slope areas. A "normal" rock fall, i.e. one not directly associated with a seismic event, involves a precise relationship between a series of static parameters, on one hand, and the accumulation area features, on the other. Gravity is the main external factor involved. When a rock fall is the direct result of an earthquake shock, the main external factor is the resultant of the force of gravity and acceleration and perhaps length of time of the quake. Somehow, this fact must be responsible for some particular features: the unusual extent of the accumulation area can be viewed as one of these features; another is the considerable size of the fragments.

3.1.1. The 1976 quake in Friuli was responsible for a large number of rockfalls. Their detailed description by Govi & Sorzana in the course of the studies of the quake made by the Italian National Research Council suggests that the abnormal features mentioned above are present in a great many instances.

3.1.2. The Friuli area displays several morphological features for which a variety of interpretations have been proposed, that could be the expression of ancient quake-induced rockfalls that have been subsequently modified to a varying extent by erosion. Their relation to other Quaternary deposits makes them post-Glacial, while their different morphology shows that they are not all of the same age, even though it is clear that they pre-date the permanent settlement of the area by man. Indeed, there is no reference to such an event in the historical documents.

Examples of these features include the heap of large blocks that shuts in the Cornino Lake, just South of Peonis, and the supposedly morainic ridges in the middle of the Resia Valley. Their composition in almost solely monogenic blocks and their geometric relations to the slopes from which they were
most probably detached are suggestive of earthquake rockfalls. As far as the Val Resia accumulations are concerned, it is clear that their present shape is due to the action of the watercourse. Both accumulations, if compared with those caused by the Friuli quake, testify by their extension the action of even stronger seismic action.

3.1.3. Some features of late-Glacial rockfall accumulations described in several places in the Alps bear a distinct resemblance to those already described. In some cases, namely the so-called "marocche" - enormous rockfall accumulations redistributed by Würmian valley glaciers during the last stages of the retreat - an earthquake may be held responsible, the stage having been already set by heavy glacier pressure, especially at the points of confluence, following the release of pressure owing to the deglaciation. A point in favour of this view is the fact that most "marocche" are found in areas with a record of high seismicity (e.g. Ravini di Marco in Val Sarca, the Vedana-Mas "marocca" in the Belluno region, etc.). An important consequence, of course, would be the interpretation of phenomena of this kind as earthquake landslides in areas held to be aseismic in the light of the historical evidence (e.g. the Carema "marocca" in the lower Aosta Valley).

3.2. Direct evidence of rupture of the ground due to earthquake, yet not followed by landslides, because of inadequacy either of slope or of acceleration, can be seen in the phenomena described as "surface faulting". These are, in fact, "active faults" of the rocky or loose materials that form the topographical surface. Nevertheless one feels that, at least as far as Italy is concerned, such faults should be distinguished from "active faults" in the true sense. They are, indeed, the result of seismic activity, and, terminologically speaking, should not be equated with "active faults", which typically are thought of as potentially seismogenetic. Furthermore, surface faulting is partly independent from normal structural evolution of the formations in which it occurs: as an evidence, a typical feature of s.f. is the constant value of slip and its modest extent with respect to the length of the break; it is, in fact, an accidental, albeit recurrent, phenomenon in the course of their normal development.

3.2.1. The "active faults" and earthquake cracks described by Bosi /4/ and by Martinis /5/ respectively in Friuli can, in effect, be referred to phenomena of this type. Their relation to the earthquake magnitude pointed out by Bosi is worthy of attention.

3.2.2. In a paper on the Tagliamento Morainic Amphitheatre neotectonics read at the Xth INQUA Conference /6/, Carraro & Petrucci described the presence of particular forms of surface deformation in this amphitheatre, consisting of en echelon "wrinkles" about one metre high and ten metres long, tentatively interpreted as the plastic response of the turf to the resettlement of water-soaked gravels, by high degree earthquakes. This may have taken place in the post-Glacial period, though
prior to permanent human settlement of the area. During the ensu-
ing discussion, R.P. Suggate mentioned that similar forms of
proven seismic origin had been observed in New Zealand, where a
link had also been established between such forms and the sub-
vertical attitude of the rocky basement.

3.2.3. "Surface faulting" must be pretty widespread in Italy.
When recognized (which occurred rarely) it has been described
as "active faults" in the light of its objective geological set-
ting. A particularly full series has been presented by Bosi for
the Abruzzi region [77].

In the case of the Tagliamento Morainic Amphitheatre
"wrinkles", collapse structures sometimes classifiable as se-
dimentary dikes can be seen within the incoherent gravels in
which they are developed; it may be supposed that the formation
of such dikes subsurface is a common feature of the establish-
ment of earthquake cracks within loose formations. Dikes of par-
ticular type, i.e. with features indicative of instant filling,
may thus be seen as evidence of such cracks, and hence as a mo-
re permanent record of what is otherwise a quickly obliterated
event.

The same explanation can perhaps be offered for other se-
dimentary dikes in seismic areas, such as these consisting of re-
cent marine sands which fill a network of fractures in the cry-
stelline basement in Calabria, and can be seen on the Tyrrhenian
coast near Scilla (Reggio Calabria) and on the Ionian coast near
Copanello (Catanzaro). Here the phenomenon obviously antedated
uplift.

If a more accurate assessment can be made of the diagno-
stic parameters for sedimentary dikes of seismic origin, their
recognition in areas thought to be earthquake-free will be of
particular interest. An example is provided by some very distin-
ctive dikes of the lower Aosta Valley found by R. Sacchi. This
is an area where evidence is being accumulated of intense neo-
tectonic activity and where some morphological signs of seismi-
city (e.g. the Carema "marocca" described above) are recogni-
izable.

3.3. Changes induced in the hydrographic network are often
listed among the effects of highest degree quakes. The generic
and summary descriptions available, indicate that this pheno-
menon is the result of tilting or, even, of ground rupture.

3.3.1. L. Broili has kindly drawn our attention to a case of
altered drainage following the Friuli quake. While of insig-
nificant proportions, this example is nevertheless of theore-
tical interest. At the E edge of the Susans relief and about
1 km W of Maiano, a small valley running straight down the fall
line on a slope composed of late-Miocene conglomerates appears
to have changed its direction at various times. One change pri-
or to the 1976 quake was due to a probable earthquake crack
that runs across for about 100 m and forms a distinct counter-
slope; the valley drainage formerly followed this natural gut-
ter. The '76 quake was responsible for the formation of another smaller crack at an angle to the previous one. Once again, the drainage has been changed and now follows the terminal section of the crack.

3.3.2. Fluvial captures and diversions are particularly common in Friuli and are often referable to neotectonic activity. Phenomena related to seismic action are commonly distinguished by the immediate nature of the event which caused them. Yet the identification of this particular feature is difficult when the result was a major hydrographical alteration. A possible example is the diversion that the Torre Stream shows S of Tanataviele. The sudden nature of the phenomenon would essentially be suggested by the decidedly under-sized transverse profile of the valley at the level of the bend when compared with the rest of the valley, and by the mass of large blocks displayed by the rock at the valley bend. A break-up of this kind could be the result of rapid movement on surface fault, such as can be seen at many places along fractures that cross peri-Adriatic over-thrust system. In the present case, diversion has taken place just S of the Musi Chain, which is well known as one of the most active branches of this system.

3.3.3. As we have already said, there is no ready a priori indication of the diagnostic features that distinguish a drainage change due to earthquake action from slow movements or variations attributable to other causes. At present, therefore, it is too early to investigate the extremely rich catalogue of hydrographical changes to be found in Italy from this standpoint. Nevertheless, very profitable results may be expected once a theoretical and analytical examination of the question is undertaken.

4. BIBLIOGRAPHIC REFERENCES


Pietro Caloi\textsuperscript{(1)} and Marcello Migani\textsuperscript{(2)}

\textbf{ABSTRACT.} - As is known, a seismic wave is intended as a movement originated at the focus of an earthquake and observed at a short or long distance. The interposed medium is only an intermediary to this movement and, at the point reached by the seismic wave, it undergoes a shift that may be either linear or orbital, depending on the nature of the transiting motion. The seismogram of a distant earthquake thus consists of oscillations that are expressions of the nature and characteristics of the oncoming waves: longitudinal, transversal, channelled, reflected, refracted, etc. or so-called "superficial" because of their path comprised between superficial earth strata or, at the most, in the lithosphere or asthenosphere.

In the propagation of seismic waves, the medium reacts in relation to its elastic characteristics, which allow the seismic wave to propagate with a certain velocity.

Of course, seismic waves behave similarly also with near or local earthquakes. In this case, however, there is a limit. The zones characterized by high seismicity or located in mountainous areas have superficial layers of the crust that are more or less thickly and deeply fractured and fissured so as to form what the Japanese call "land blocks". In addition, also mountain ranges -- real mosaics of sub-vertical elements -- contribute to form a block structure in which the blocks may possess a certain degree of freedom in movement.

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In these conditions, earthquakes of a certain intensity (with a magnitude not exceeding 4-4.5) cause ordinary seismic waves that propagate as if the medium were continuous, as the medium is only the means of transit of the seismic energy. Hundreds of examples were provided in this connection by the Friuli area, particularly during the 1976 crisis.

But if the earthquake intensity at the focus can overcome the cohesion forces that hold the faulted surface structure together, then the structure will not act merely as a means of transit for the seismic waves; shaken more or less violently by the seismic energy, it reacts with its own movements which superimpose their activity, consisting in general by flexural waves, on the activity of the seismic waves proper. To our knowledge, this is the first paper that deals with these violent movements superimposed on ordinary seismic waves, with special reference to the catastrophic earthquake that occurred on May 6, 1976 in Friuli, where the phenomenon assumed unexpected proportions.

**RESUME** - Par onde sismique on entend un mouvement né à l'hypocentre d'un tremblement de terre observé à petite et à grande distance. Le moyen interposé sert d'intermédiaire à ce mouvement et effectue un certain déplacement - qui peut être rectiligne ou orbital - selon la nature du mouvement en transit.

Le séismogramme d'un tremblement de terre lointain consiste donc d'oscillations qui sont l'expression de la nature et des caractéristiques des ondes qui arrivent: longitudinales, transversales, canalisées, refléctées, réfractées, etc., ou superficielles, ainsi dites à cause de leur parcours, compris dans les stratifications superficielles terrestres ou, tout au plus, dans la lithosphère ou dans l'atmosphère.

Dans la propagations des ondes sismiques, le moyen intervient donc en fonction de ses caractéristiques élastiques qui permettent aux ondes sismiques de se propager à une vitesse déterminée.
Naturellement, les ondes sismiques des tremblements de terre voisins ou locaux ont un comportement analogue. Mais ici il y a une limite. Les zones caractérisées par une sismicité élevée et placées en régions montueuses ont les stratifications superficielles de la croûte faillées et crevassées plus ou moins dru ou profondément, de façon à former ceux que les japonaises appellent "land blocks". En outre, aussi les systèmes montueux, qui représentent d'autentiques mosaïques d'éléments sub verticaux, contribuent à former une structure à blocs ayant une certaine indépendance de mouvements.

Des tremblements de terre d'une certaine intensité (magnitude maximale 4 - 4.5) provoquent, même dans les situations illustrées ci-dessus, des ondes sismiques ordinaires se propageant comme dans un moyen continu qui sert donc d'intermédiaire au passage de l'énergie sismique. La zone du Friuli a fourni des centaines d'exemples à ce propos, en particulier pendant la crise de 1976.

Lorsque l'intensité du tremblement de terre à l'hypocentre est telle à vaincre les forces de cohésion de la structure superficielle faillée, cette dernière ne se limite pas à faire d'intermédiaire au passage des ondes sismiques mais, ébranlée plus ou moins violemment par l'énergie sismique, réagit par des mouvements propres qui superposent leur activité formée, en général, par des "flexuralwaves", à celle des ondes sismiques proprement dites.

Dans ce rapport on traite - pour la première fois, que nous sachions - justement les mouvements violents superposés aux ondes sismiques ordinaires et en particulier du fort tremblement de terre du 6 mai 1976 en Friuli où ce phénomène a eu des aspects insoupçonnés.
1.- In seismology, a seismogram is conceived as the aggregate of the movements performed by the instrument under the action of the seismic energy released by an upset of the equilibrium in the focus area. In other words, seismology studies the shifting of solid particles reached by the seismic perturbation, and the direction and path of these movements will differ depending on the nature of the seismic wave reaching the particles. These particles will thus move in the direction of the wave propagation (longitudinal waves), along a plane orthogonal to it (transverse waves), and in the direction orthogonal to the direction of propagation in transverse-tangential waves (without a vertical component); in addition, the particles will undergo the same type of movements under the action of reflected or refracted waves of the same type or a combination of the various types, and of channelled waves.

Then we have the movements due to the so-called surface waves: Love waves (transverse-tangential) and Rayleigh waves. The latter cause the particles to perform a backward elliptical path. \(^{(n)}\)

\(^{(n)}\) It should be pointed out that the origin of classical Rayleigh waves is limited to a short-radius annulus in which the longitudinal waves
We have not considered Stonley waves, which rarely form, and the waves called "Somigliana" by Caloi which form at minimal distances of a few hundreds of kilometers as they require a particular angle of incidence to form.

When the earthquake occurs at a short distance or even locally -- as was the case of the Friuli earthquake in respect of the recording stations located there -- all these longitudinal, transverse, reflected, refracted, superficial and other waves cause movements that are extinguished in a few tens of seconds (Fig. 1).

2. In the foregoing statements we assumed that the medium in which the equilibrium was upset -- regardless of the mode -- acts only as a means of transit for the elastic movement that hits it from every direction thus causing the particles to undergo displacements in every which way. In other words, the medium transmits the movement according to the law of elastic wave propagation. This is true for all earthquakes except high-intensity earthquakes at a short distance.

Let us compare, for instance, the seismograms in Fig. 1 and Fig. 2, both of which come from the same epicentral area. The seismograms in Fig. 1 are a local recording of the first aftershock of the May 6 earthquake, and those in Fig. 2 are a recording of the earthquake itself taken at Palisades, N.J. Of course, the epicentral distance differ: the epicenter may combine with a transverse wave. The Rayleigh waves proper originate at a considerable distance from the focus, as demonstrated by the Japanese researchers, Nakano and Sezawa, in extending Rayleigh's theory to stratified media.
of the aftershock was 54 km away from the Vajont recording station, and the epicenter of the earthquake was at a distance of 6600 km from the Palisades station.

Notwithstanding the appearance, these two sets of recording have substantial points in common: both consist of longitudinal, transverse, combined, reflected and other waves. The first set of recordings refers to waves conveyed by the superficial layers \((P, S, \ldots)\); the second set refers to waves that involved the mantle \((P, PP, \ldots, S, SS, \ldots)\).

Both sets contain Love waves and Rayleigh waves (the waves recorded at Palisades were originated in the surface layers of the crust). Moreover, the Palisades recordings present samples of \(C_{0,1}\) waves studied by Caloi and caused by SV waves impinging on the bottom of the earth crust from effective angles.

Let us take a much more important step forward. Let us compare the above mentioned sets of recordings with the seismograms obtained at Vajont at the time of the main shock, which was recorded at Palisades. The \(P\) and \(S\) waves took the same time to reach the Vajont recording station as the aftershock, which is natural since the distance and the speed are the same. \(\text{(fig.3)}\)

Thereafter, however, no comparison is possible. The gallop of vibrations that disturbed the Vajont station on May 6 and continued for over sixty minutes finds no counterpart in the aftershock; not only, but what is more surprising is that these prolonged violent perturbations were not present in the Palisades recording, not even in traces.

Therefore, the main shock determined perturbations that cannot be classified entirely as seismic; there is a considerable component due to other vibrational systems, which are normally neglected. Over a
certain magnitude, the stricken medium no longer acts merely as a means of transit for the seismic energy, but it reacts with its own system of actions -- which are not only elastic -- over a wide area around the epicenter.

3. It is therefore to the vertical structure of the earth's crust that we must direct our attention. We consider the earth's crust as a stratification of two or three layers on the average, each of which is limited by surfaces that are more or less parallel to the external surface. It is in this manner that the greatest success has been achieved in understanding the physical, and especially the elastic, characteristics of the earth's crust and of the structures at depth as well.

The application of the elasticity theory to seismic waves has yielded a host of results and it is essentially the source of all we know on the insides of the earth. Therefore, homogeneous strata in a compact continuous medium. But if this is true for the part of the earth underlying the crust, it is only a rough approximation for long stretches of the crust. Indeed, in high-seismicity and mountainous areas, pronounced radial discontinuities are often present. The merit of studying fractures in general in high-seismicity areas goes to the Japanese, particularly to Miyabe.

It has often been observed that the curves representing the displacement in height of the benchmarks along a given leveling line are not always continuous; they often appear in straight segments. This indicates that the portions of the crust that are bounded by recent faults are subject to upthrust or downthrust as a block without undergoing appreciable deformation. These portions are called "land blocks" and they were noticed in Japan during the geodetic investigations.
carried out after several earthquakes; in fact, they led the Japanese researchers to believe that in seismic areas the superficial layer of the earth's crust is broken up into relatively small blocks that move independently from one another.

N. Miyabe succeeded in determining the position of the blocks by means of the data relating to points located on an inclined plane in a certain direction. Let $a$, $b$, $c$ be these points (Fig. 4), $\theta$ the inclination of the plane on which they are located, and $\varphi$ the angle of the plane direction in respect of the north. Let $h_a$, $h_b$, $h_c$ be the displacements in height of each point; $\varphi_{ab}$, $\varphi_{bc}$ etc. the azimuth of the segments connecting $a$ to $b$, $b$ to $c$, etc.; and $\theta_{ab}$, $\theta_{bc}$ ... their inclination. Thus we obtain (2):

$$\tan \theta_{ab} = \frac{h_a - h_b}{a - b} = \tan \varphi \cdot \cos (\varphi_{ab} - \varphi)$$

$$\tan \theta_{bc} = \frac{h_b - h_c}{b - c} = \tan \varphi \cdot \cos (\varphi_{bc} - \varphi)$$

Let us plot the points having $\varphi_{ab}$ as an abscissa and $\theta_{ab}$ as an ordinate. If the points lie on a plane, that must spread out along a sinusoidal curve having an amplitude $\varphi$ and a phase $\varphi$. When the change in height of a benchmark does not fall on the sinusoidal curve it is to be assumed that the corresponding point lies on a different land block.

N. Miyabe applied this method to the results of the geodetic measurement campaigns carried out in seismic or volcanic areas and succeeded in demonstrating the existence of numerous blocks.

We shall only point out an example in which sinusoids are clearly outlined (Fig. 5, 5 bis) and witness to the existence of individual blocks $\varphi$, and reproduce the
blocks in the Sagamino area as established by Miyabe (fig. 6). Japanese seismologists accepted Miyabe's conclusions; a few, though convinced that the existence of the blocks is unquestionable, are of the opinion that the actual number of crustal blocks is smaller than that calculated by Miyabe.

According to the Japanese, these crustal blocks in seismic areas are relatively small, having diameters on the order of 7-14 meters and thicknesses on the same order as their average horizontal dimension. These blocks move independently from one another.

The surprising thing is that the Japanese seismologists limited their investigations on the blocks to the only purpose of proving their existence, by studying their behaviour after an earthquake.

These studies on land blocks were not continued in other parts of the world. Only in Italy, on various occasions, have we availed ourselves of clinographic observations over appropriate lengths of time in order to establish whether an area selected as a prospective dam site was all on one block or not. These clinographic investigations were extended as far as the foot of the Bellunese and Carniche Alps, and they were always accompanied by geoseismic investigations to establish the main characteristics of the rock. It was the latter investigations, however, that led us to the conviction that the Pre-Alps we investigated are real mosaics, in that small areas with certain characteristics are surrounded by others that have a completely different geodynamic behaviour (3).
4. Since the Upper Friuli, both as a highly faulted seismic area and as a mountainous area was very likely to have a distribution of vertical blocks, it was to be expected that a strong quake would have a markedly abnormal behaviour from an elastic standpoint. As long as the strong lateral pressures keep the various elements of the surface layers of the earth's crust closely together, earthquakes of limited magnitude find a means that can only transmit the seismic movement. In this case, the recording contains only seismic waves of the $P_g$, $S_g$, $P_g$, $Q(L)$, etc., as shown in Fig. But if the quake releases enough energy to overcome cohesion, then the medium no longer acts as a mere means of transit for the seismic waves (longitudinal, transverse, etc.), but it reacts with its own movements and adds its own oscillations to the seismic waves proper. And this is what occurred to a large extent in the Friuli earthquake on May 6, 1976.

Let us consider the recording of the quake shown in Fig. 3 obtained at Vajont. At a first glance, any comparison appears to be impossible. The similitudes are very little and concern mainly the $P_g$ and $S_g$ waves. Of course, with equal travelling times, also the $Q(L)$ waves and the classical Rayleigh waves would be recorded, but their amplitude did not permit it. From a seismologic standpoint, however, the recording would have terminated in a few tens of seconds. The enormous tail of oscillations that lasted at least an hour and three quarters is an extraordinary addition due to the movements of the aggregate of subvertical elements (geodetic blocks, mountainous pillars and related roots, etc.) that constitute the upper layer of the earth crust in the epicentral area. It should be emphasized that these movements do not follow the laws that govern the
propagation of elastic waves.

A proof can be supplied by comparing the Vajont recordings with the recording of the same quake at a distant station, for instance, with the recordings taken at Palisades at the Lamont Observatory of the Columbia University. As earlier stated, Palisades is at 6680 km from the epicenter versus the 54 km of the Vajont station. The Palisades recording is quite normal, and is as expected for an earthquake at normal depth and at that distance: P waves, traces of PP waves, S waves and excellent examples of $C_{0,1}$ -- waves induced in the earth's crust by SV waves inciding at effective angles, as demonstrated by Caloi -- SS waves and similar $C_{1,2}$ waves and, finally, distinct L waves, which are missing on the vertical as they are transverse-tangential waves, and a clear tail of R waves in the theory.

The Palisades recording shows no signs of this enormous tail of oscillations: that appear to predominate in the Vajont recording after the L and R waves of the external layer; the earth's crust has absorbed them all. This fact can be explained by admitting that these oscillations are of a different nature and are not really seismic.

With reference to the blocks identified by seismologists in seismic areas, since they are considered to be relatively small and of a thickness that does not differ much from their horizontal length, when these blocks are struck by seismic energy released at the focus they behave like prismatic bars, fixed at the bottom and stressed to bend perpendicularly to its generatrices; they will thus be stressed to perform free transverse oscillations, which are called flexural waves.
Of course, we shall not dwell on theoretical considerations, also because in view of the complexity of the problem they could be but very approximate. One of the authors has developed a theory some time ago\(^4\) on the free oscillations of the pour of a dam. Since these are finite elements, the theory of the propagation of elastic waves in unlimited media does not apply. Thus the longitudinal wave propagation speed in the bar will be expressed by \(\sqrt{\frac{E}{\rho}}\), in which \(E\) is Young's modulus and \(\rho\) is the density of the element considered. In conclusion, for the propagation speed \(V\) of the transverse oscillation we shall have:

\[
V^2 = \frac{2\pi}{T} \sqrt{\frac{E}{\rho} \frac{I}{A}},
\]

where \(T\) is the period of the oscillation considered, \(I\) the moment of inertia of the straight section in respect of the normal to the base plant at its center. For a rectangular transverse section having a width \(a\) and a thickness \(b\), we have

\[
\frac{I}{a} = \frac{b^2}{12}.
\]

Therefore

\[
V^2 = \frac{\pi}{T} \sqrt{\frac{E}{\rho}} \cdot \frac{L}{2\sqrt{b}} \quad (4)
\]

As a result, it can be demonstrated\(^4\) that

\[
T = \frac{4\pi \sqrt{3}}{V^2} \cdot \frac{L}{b} \cdot \frac{1}{\sqrt{E/\rho}} \quad (2)
\]

where \(L\) is the height of the stricken block and \(V\) one of the solutions of the motion equation. As to the order of magnitude, the roots assume the following values\(^4\):

\[
1.17 \frac{\pi}{L}, \quad 2.93 \frac{\pi}{2}, \quad 5 \frac{\pi}{2}
\]
Eqn 2 provides the values of the periods of the free mononodal, binodal, etc., transverse waves when the data of the problem and the roots of the motion equation given above are known.

Without performing the calculation, it will be readily seen from Eq 1 that the propagation speed of the free oscillations of the stricken pillars is inversely proportional to the square root of the period. As a result, contrary to what occurs with Love and Rayleigh waves proper, this particular type of oscillation delays as the period becomes longer.

Therefore, the Love and Rayleigh waves in the Palisades recording having nothing to do with the oscillations that form the body of the seismograms taken at the monitoring stations in the epicentral area.

However rough the approximation may be, let us consider the following example. For a geodetic block with a width 1 of 4 km and a thickness b of 4 km and assuming for the superficial layers \( \sqrt{E/\rho} \) = 7 km/sec, we obtain \( T = 5 \) s for the mononodal and \( T = 1 \) s for the binodal; the respective speeds of the flexural waves are 2.7 km/s for the mononodal and about 6 km/s for the binodal. Of course, by varying the terms, we may obtain as many values as we wish.

It is presumable that the mononodal waves are the flexural waves that undergo the largest movements. There is a first group of flexural waves that terminate in a couple of minutes and are evidently related to very small elements with periods on the order of 1-1.5 s; these are strongly amplified by the instruments that give the maximum amplifications for those periods (20-25 times greater than the enlargements for periods of 5 s). Then follow well-promounced groups with increasing periods associated with oscillating elements that originate aperiodical oscillations. It may happen that one of the oscillating groups having
a certain period precedes a group with a slightly shorter period; this is simply due to the fact that the first oscillating group is appreciably nearer the recording station than the second.

The law illustrated above is, however, verified: the flexural waves of the longer-period oscillating elements propagate at a slower speed. Thus, while the flexural waves with period on the order of 5 s are recorded at the Vajont station about 7 min after the beginning of the recording, those with periods of 7-6 s arrive at the same station about twenty minutes after the beginning of the recording, and those with periods of 10-12 s (which are of course the narrowest because they are the least amplified by the instrument) arrive about 45 min after the beginning of the recording.

Of course, the statements made for the Vajont recording station apply also (fig. 7) (and possibly more clearly) to the stations of La Meina (at 36 km), Pieve di Cadore (at 55 km), Ambiesta (at only 15 km), etc.

The distinct superimposition of the oscillations of groups of elements in local superficial layers of the earth's crust under a violent stress over the properly seismic recordings persists in the recording stations closer to the epicenter and is always the main phenomenon. As the distance from the epicenter increases and the convulsive local perturbation fades out, the seismograms tend to assume a more normal appearance. Thus at Monte Porzio, Rome, there appears initially a real tangle of seismic waves proper and superimposed oscillations. In longer-period instruments ($T_1 = 15$ s, $T_g = 100$ s), Rayleigh waves that were forming in the layers of the earth crust distinctly appear after a certain time. However, in order to obtain a seismologically normal recording, it is necessary to go farther away from the epicenter. As we have seen, the Palisades recording is a pure, textbook seismogram.
5.- The foregoing clearly demonstrates that in the focal area of a high-intensity earthquake in a highly faulted area combined with mountainous systems, the merely seismic manifestations that are bound to propagate the farthest, such as rare waves and superficial waves, do not extinguish the local movements when the seismic energy released at the focus is capable of giving rise to a tumultuous upheaval of sub-vertical superficial elements that no longer retain the function of a means of transit for the seismic waves, but add their own violent flexural waves, which excite other elements and persist for several tens of minutes.

Of course, in view of the particular mode of oscillation, these strictly superficial movements are extinguished in a few kilometers' distance and do not appear at all on the seismograms of distant recording stations. They are, however, in our opinion, extremely interesting for an understanding of local geodynamics, which are closely linked to construction science.
REFERENCES


Fig. 1 - One of the many aftershocks of the May 6, 1976 earthquake recorded at the Vajont (vertical component, May 7, 1976, 10h 43 min.): same epicentral distance as in the main shock ($\Delta = 54$ km) and same succession of $P_g$, $S_R$ and associated waves and of classical Rayleigh waves.

Fig. 2 - The Palisades recording (NS component) taken at 6636 km consists of seismograms such as are recorded at that distance for normal depths. Evident arrival of $P$, $PP$ ($P_a$), $S$, $C_o$, $S_{11}$, $SS$, $C_{12}$, $S_{12}$, $L$ and $R$ waves. This is obviously the main shock. The Love and Rayleigh waves proper are, of course, subject to normal dispersion.

Notwithstanding the high amplification of the Palisades instruments, the recording extinguishes in less than two hours; they recorded only the seismic waves proper.

For instance, it should be noted that the longitudinal waves of the vertical component of the quake recorded at Vajont (Fig. 3) started with an actual displacement of about 1 micron, whereas flexural waves with a period of 6 s later caused actual displacements of about 17 microns. Nevertheless, the former arrived as far as Palisades (and farther), while the latter were extinguished at a few hundred km from the epicenter. This proves the different nature of the two wave types: the first, a spatial wave, with a slight attenuation; the second, a superficial oscillation, destined to be absorbed rapidly.

Fig. 3 - The aftershock shown in Fig. 1 and the many other aftershocks have in common the strictly seismic characteristic. What was recorded at Vajont on May 6 about 3 min after the beginning of the main shock was the pseudoseismic disturbance of the superficial fractured structures in the epicentral area caused by the energy of the shock, which broke the continuity of the medium and transformed the groups of sub-vertical elements into as many sources of flexural waves (vertical component).
This explains also the enormous duration of the recording which lasted for about two hours and contained oscillations that varied in period between 2 s to 10 s.

It should be noted that the Press-Erwing instrument at Palisades (Fig. 2), whose characteristics were particularly suited for the recording of short-frequency waves \((T_C = 30 \text{ s}; T_G = 100 \text{ s})\) had terminated the recording of the Love waves on the NS component 32 min after the beginning of the shock. At the local ENEL recording stations (Ambiesta, La Maina, etc.) notwithstanding the limited amplification of periods over 3-4 sec., the local pseudo-seismic movement lasted more than an hour and a half.

Fig. 5 and 5 bis - Examples of land blocks identified by Miyabe along the routes of geodetic investigations carried out on the soil after an earthquake.
fig.1bis - La Maina - 7/5/76

Limite superiore intensità, cui corrisponde ancora esclusiva trasmissione onde sismiche da parte del mezzo.

Upper intensity limit, at which the medium still transmits only seismic waves.
Fig. 5
Fig. 5 bis
GROUND CRACKS CAUSED BY THE FRIULI EARTHQUAKE, 1976,
FROM M. CUARNAN AND TREMUGNA VALLEY (*)

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Abstract. Among the ground cracks caused by the Friuli earthquake those located on the southern slope of M. Cuarnàn and in the Tremugna Valley have been investigated. In the first locality the ground cracks were increased by the seismic shocks of September 15, 1977. Areas, in which ground cracks occurred, have been surveyed in detail and surficial deposits, bedrock and morphological characters were mapped at large scale. These ground cracks have been interpreted as originated by landslides triggered by the earthquake.


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1. FOREWORD

The geological effects of the Friuli earthquake reported in various parts of Friuli included cracks in the ground that appeared, especially, as the result of the tremors of 6th May [1].

The most spectacular of these, located on the southern slope of Mounts Cuarnàn and Cuar, were the subject of study by Bosi et al. [2] and by the CNEN–ENEL commission [3]. According to the letter, these cracks might have been due either to landslides or to tectonic displacements; in the second case, a "seismogenetic structure" would be found striking east–west, corresponding to the large displacement that crosses the whole of Friuli and is known as the Periadriatic overthrust. However, again in the opinion of Bosi et al., the cracks would be the only phenomena that might constitute surficial and macroscopic evidence of movement along the faults on the occasion of the earthquake.

The technical experts of the CNEN–ENEL Commission are inclined to rule out any cause associated with landslides, and would attribute the cracks to "surficial differential movement of limestone blocks, which are extensively cracked due to their proximity to the overthrust surface; differential movement occurring along pre–existing fracture planes and due to the different response to seismic stresses on the part of rocky blocks situated near the rear edge formed by the mesozoic carbonatic rocks".

The above interpretation gives rise to some perplexity, especially if we compare the cracks in question with others reported in the region, similar in their characteristics yet of clearly different origin. Since this interpretation is particularly significant if it can be confirmed, however, we have thought it advisable to reexamine the cracks on Mounts Cuarnàn and Cuar, collecting further information on the subject but especially, setting such information in its local geologic context. The observations that follow were made on the occasion of on–the–spot surveys conducted after the earthquakes of 6th May and 15th September, while the geologic survey was made in August of this year.

2. MOUNT CUARNAN GROUND CRACKS

2.1 Geologic setting

In the area in question, apart from surficial deposits, there are also outcrops of mesozoic carbonatic units and Flysch of the Paleogene period. The carbonatic units consists of: clear dolomites (Haupt Dolomites) in layers ranging from 50 cm to 2 m and of Norian–Rhaetian age; oolitic, intraclastic,
and bioclastic calcarenites, and calcilutites mainly beige in
colour, in layers 10 to 100 cm thick of Lias-Lower Malm age;
calcilutites (Soccher Limestone), whitish beige or greyish in
colour, with intercalations of calcarenites and sometimes
calciuridites, in layers of a few centimetres up to a metre,
with nodules, bands and small layers of chart, of Lower Malm
Lower Cretaceous age. The Flysch consist of sandstones with
subordinate marls, conglomerates and calcarenites (Stregna
Flysch), which, in an upward direction, becomes an alternation
of marls and sandstones, with subordinate layers of carbonatic-
cherty pudding-stones (Cormòns Flysch) and of an age ranging
from the Upper Paleocene to the Eocene.

The surficial deposits, which sometimes completely cover the
units described above, are represented especially by alluvial
cones and deposits, glacial deposits, talus heap and talus
cones.

Structurally, the area may be subdivided into three parts:
the dolomitic mass of Mount Chiampòn, with monocline dipping
northward, which overthrusts the mesozoic succession of Mounts
Cuarnàn and Glemina, which, in its turn, overthrusts the Stregna
Flysch. The overthrust planes strike east west, and dip
northward. The first, so-called Periadiatic overthrust is the
main one, inasmuch as the carbonatic mass of Mounts Cuarnàn
and Glemina may be considered one tectonic block, albeit of
large dimensions, in which other smaller blocks can be distin-
guished.

2.2 Ground crack features

The ground cracks are located on the southern slope of Mount
Cuarnàn, at 820-970 m, and extend over a front of about 600 m.
At an altitude of about 800-900 m, there is a sudden break in
the steep slope, with an ondulate surface and local counter-
slopes.

The bedrock consists, in its upper part, of beige-
coloured calcilutites, with bands and chert nodules (Soccher
Limestone) and, in its lower part, of carbonatic Flysch (Stregna
Flysch), only two outcrops of which were observed at 800
and 900 m, respectively.

The tectonic contacts between these two units, along a plane
dipping down to northward and slightly sloping, is masked by
surficial deposits. These consist of: calcareous-dolomitic
talus heap with pieces measuring not more than 10-20 cm, of
variable thickness, most prevalent in valley floors, and of rear-
anged, locally cemented, scree, again with calcareous-dolomi-
tic elements, in blocks of 10-20 cm, which can be assimilated
with old landslide debris heap, now become stable. These surfi-
cial deposits have brown soil, 10-30 cm thick, and sometimes
only a few centimetres.
The lowest ground cracks are found at an altitude of between 810 and 860 m, on the outer edge of the plain; they strike N 50° E or N 80° E, parallel to the mountain slope, with a horizontal displacement of 10–20 cm, oblique displacement of 20–30 cm, and depth of about 1 m. The bottom of these ground cracks, like that of others that will be described further on, was, at the date of the last observations (August 1977) filled with small debris.

At a height of 875–890 m, the ground cracks are somewhat varied in strike, sometimes following a line of jagged cemented carbonatic, monogenic debris, in this case, too, along the outer edge of the plain. The presence of calcitic smears and incrustation on the breaks suggests that the ground cracks existed before. Collapse of 30–40 cm was noted in the lower part, with horizontal displacement of 30 cm. Laterally, the displacement disappear after a few metres, 10 m at the most.

Between the altitudes of 900 and 950 m, the mountain slope is steeper and more gently modeled by valley floors and straight spurs, parallel to the spur which descends to 1062 m. Here we have the largest ground cracks, with an "en echelon" pattern and interruptions, especially in the valley floors. These ground cracks, whose slope of 70–80° is greater than that of the mountainside, strike approximately east-west, corresponding to the spur at 1062 m, where breaks striking north-south can also be found. To eastward of the spur, the general direction is WNW-ESE, and the displacement varies up to a maximum of 150 cm; this is higher in the spurs, while it is less in the valley floor, where sometimes the ground cracks disappear altogether. The displacement is towards the valley; only in one case, as reported by Bosi et al. [2], is it 20 cm in an upward direction.

The deposits affected consist exclusively of calcareous-dolomitic talus heap, and only in one case was the bedrock uncovered. At some points, the downhill side appeared to be swollen. A few measuring instruments, placed after the 6th of May, may be possible to identify a further widening of the ground cracks after the tremors of 15th September, though this was extremely local, and the maximum value observed was 40 cm.

2.3 Genesis considerations

The ground cracks in Mount Cuarnàn may be subdivided into two types: those bordered by the ondulate surface, between 810 and 890 m, and those on the steep slope, between 900 and 950 m. They are distinguished from each other by the nature of the deposits concerned as well as by their morphological features.

In the first case, the deposits involved, which cover the Flysch formation, are locally cemented landslide debris heaps, several metres thick, with calcareous-dolomitic, normally coarse, and calcarenites elements. The ground cracks occurred on the outer edge of the plain, and are therefore clearly associated with the action of gravity; moreover, they are sometimes located
on pre-existing fractures, shown by the presence of calcitic incrustations along the walls of the crack. They therefore have the features of numerous other ground cracks observed in the area most affected by the earthquake near steep slopes, where they have also led to rockfall. In the case in question, the southernmost ground crack, recorded between 820 and 860 m, caused, not for seismic cause, the recent fall of a mass of debris, which, however, did not uncover the bedrock.

In the second case, the ground cracks are based on talus heaps, which cover the cherty limestone intermittently, giving rise to pockets and strips of varying extent and strength, which may represent the remains of a single stratum that has subsequently been eroded and has partially slipped southward. The ground cracks appear to depend on the type of the deposit and on its features. Indeed, they are only found where there is talus debris and peter out where the bedrock outcrops. At no point of the slope was it therefore possible to observe the situation illustrated in the geological section made by the CNEEN-ENEL Commission [3], in which the ground cracks recorded make deep inroads into the limestones located upward of the Periadriatic overthrust, which here, moreover, is quite invisible, because it is completely masked by the talus heaps.

In addition, in this sector, the dimensions of the ground cracks increase where they correspond to the spurs, while they become smaller to even to the point of disappearing altogether at the valley floor, where the accumulation of talus heaps appears to be greater. The most obvious example is that of the spur, which descends from 1062 m, where the ground cracks are more frequent than elsewhere, and the layer of debris is certainly less thick. In confirmation of this last statement, we have not only the morphological features, but also the presence, at the foot of the spur, at 900 m, of a very modest outcrop of Flysch - the only one in the stretch of slope under investigation.

The ground cracks recorded on the steep slope show extremely variable interruptions, echelons and displacements, which drop to only a few centimetres over a distance of a few metres. Further on, too, the movement due to the tremor of 15th September was extremely localized, with displacements of 30-40 cm at some points, while the downward displacements were limited to a few centimetres.

The swellings observed just downward of the ground cracks show that the layer of debris settled down by slipping on the bedrock, or inside the talus debris itself. The downward slip of the blocks would also explain the upward displacement, which was observed in a ground crack that opened on the spur at 1062 m.

From what has been said, it may be concluded that no fact has been produced that would make it possible to connect the ground cracks of Mount Cuarnan with any deep-seated seismogenetic phenomenon. We tend rather to the opinion that the ground cracks are a surficial effect of the stresses produced by the earthquake.
which tend to detach the talus heap from a steeply sloping bedrock. Movements of this kind, irrespective of any earthquake actions, have occurred in the area in the past—perhaps several times; they have given rise to the undulate surface, already mentioned, whose morphology, together with the chaotic setting of the material, indicates an accumulation due to rock fall from the steep slope above.

3. THE TREMUGNA VALLEY GROUND CRACKS

3.1 Geologic setting

The area in question is situated between Mounts Cuar and Covria on the north side, and Cima Pala on the south, and the Mount Prât plateau on the south-west side, separated by the Tremugna Valley and the Tochèl Valley.

On the high ground, mesozoic carbonate rocks outcrop, while, in the Tremugna Valley depression, the terrigenous bedrock belongs to the Paleogene period.

The carbonate formation consists of: clear dolomites belonging to the Haupt-Dolomite and of Norian-Rhaetian age; a succession of oolitic limestones, calcarenites, and calcilitites, with cherty lenses and levels, well bedded and of Lias-Malm age; solid limestones of the Tithonian (Ellipsactinia limestone); compact, greyish or white limestones in layers of one or more metres, of the Cretaceous. NW of Mount Covria, two small streaks of reddish marl (Scaglia rossa) of the Upper Maastrichtian-Lower Paleocene age outcrop.

In terrigenous units, we find alternating marl, silty clay, and sandstone, in thick layers 5 cm to 2 m thick, of the Upper Paleocene-Middle Eocene (Clauzetto Flysch) and breccias with coarse carbonate elements in a sandstone-marly matrix, with sandstone-clayey levels of the Lower Oligocene (Peònis breccias), and alternating sandstone, puddingstones, marl and clay, containing lignite locally, of the Middle Oligocene (Rio Tremugna sandstones and marls).

The units quoted above are locally covered by slope alluvial and moraine deposits.

The tectonics are complex, and in our opinion present features different from those given in the schematic geological map produced by the CNEN-ENEL Commission [3]. The Cretaceous limestones of Cima Pala and the terrigenous units of the Tremugna Valley constitute an autochthonous mass, overthrust both by the Jurassic sandstones of Mount Prât and by the mesozoic succession of Mounts Cuar and Covria, where the plane of discontinuity (Periadiacic overthrust) dips to the north and strikes east-west.

Connected with this overthrust, there is tectonic shingle, striking out east-west, consisting of Ellipsactinia limestone, between the Haupt-Dolomite and the Tertiary terrigenous units,
in the same way, although with smaller dimensions, as already
found on Mount Cuarnàn. In addition, there are numerous faults
striking NW-SE and belonging, therefore, to the dinaric system.

3.2 Ground crack features

The Tremugna Valley ground cracks are found on the southern
slope of Mount Cuar, between 650 and 740 m.

The morphology of the area has general features reminiscent
of Mount Cuarnàn with one steep slope (38°), interrupted to the
south, between 650 and 700 m, by a plateau, with depressions,
bulges, and counterslopes, beyond which the slope returns to a
fairly uniform slope of about 23°. A small valley striking east-
west is situated between 725 and 775 m.

Here, lithotypes belonging to the Haupt-Dolomite outcrop, upward
from the small valley, and Ellipeactinia limestone between the
small valley and the break in the slope, and to the Rio Tremugna
marls and sandstones further downward. The contacts between
these three units are masked by surficial deposits consisting of:
active talus heap, fed by the Haupt-Dolomite cataclasite, stabi-
лизed talus heap with small carbonate elements that connect the
carbonate rocks to the break in the slope, where there is talus
heap with coarse elements, which have been reworked and can be
assimilated with landslide debris in the same way as already
described for Mount Cuarnàn. These deposits are at present the
site of considerable landslide phenomena.

The ground crack further south develops at about 650 m, on
the outer edge of the plateau of coarse carbonate debris; it is
20-50 cm wide, with very variable depth and displacements of up
to 2 m, with a development of about 100 m.

Some minor ground cracks, a few tens of metres long, are
developing at the edges of and inside the plateau in the neigh-
bourhood of the house at 600 m. These have occurred in landslide
deposits, have a maximum displacement of a few tens of centime-
tres, and coincide with depressions and bulges in the ground.

The largest ground crack, at a maximum of 740 m and a minimum
of 680 m, has a development of about 400 m, with the maximum
displacement of 350 cm, and an average of 200 cm.

At its extremities, the displacement gradually peters out.
Throughout the whole of its length, there are talus heaps; only
at two points, are these actually in contact with the bedrock.
The part below is the lowered part, except for the western
extremity, where a rise of about 10-20 cm, with small bulges,
took place.

In the higher part, at 740 m, grey mud comes to the surface,
with the presence of ferrous oxides and small lignite-bearing
areas, resting on debris made up of jagged carbonate elements
measuring 5-10 cm.
3.3 Genesis considerations

The ground cracks in Tremugna Valley may also be subdivided into two types: the main crack and the other ones. The latter involved the landslide deposits on the outer edge of the plain, or coinciding with depressions. They are therefore connected with the movements of surficial deposits due to the action of gravity. It may definitely be stated that their genesis is connected with landslide phenomena caused by stresses undergone at the same time as the earthquake.

The biggest ground crack occurred in talus heap and in certain sectors (at 690 m and 700 m) that were actually in contact with the bedrock, which was laid bare. The trend of the crack is not continuous; there is a sudden interruption at 740 m, with resumption a few metres further down, where the strike also changes; however, it develops in parallel to the contact of the surficial deposits with the carbonatic rocks.

The presence of bulges further down, and especially the rise of the part below the western sector suggests detachment of the talus heap and a slight downward slip. In this case too, therefore, as in the case of Mount Cuarnân, we did not find any sure evidence of a connection of the phenomenon with cracks in the bedrock made active by the earthquake.

The area involved by the phenomenon can be clearly delineated morphologically speaking, south of the main ground crack, by an affluent of the Rio delle Tovi to the west and by the Rio Chiaraderar to the east; it consists of outcrop exclusively of talus heap, which rest, as they become thinner, on the mountain slope, which shows that in the past the area was the site of considerable derangement, subsequently stabilized. The tremors of 6th May imposed a stress on this mass of debris, above all opening up a crack with an irregular strike near the contact between the mass itself and its bedrock, and causing a slip southwards. These movements enabled the derangement once more to become active. Indeed, at the present time, a vast area between 670 and 600 m, looking on to the affluent of the Rio delle Tovi, and another smaller one further east are involved in various landslides that took place after the earthquake and are still active, and that involve a slope covered with grassy vegetation that has therefore been stabilized for some time.

4. CONCLUSIONS

Analysis of the ground cracks that occurred at the same time as the Friuli earthquake on the southern slopes of Mounts Cuarnân and Cuar, when set within the local geologic and morphologic situation, lead us to attribute their genesis to landslide phenomena rather than to indications of movement along faults in two sectors of the Periadriatic overthrust.
This is based on the following considerations:

- The trend of the cracks is not continuous, as in generally observed in movements along faults [4-5-6], but is frequently interrupted by variations in strike that may even be quite sudden, and that it is therefore difficult to attribute to a plane surface.

- The displacements are extremely variable, and the only component is the one along the maximum slope line, which is therefore associated with the force of gravity; in the rare cases of rising up of a block further down, it appears evident that the phenomenon is due to a bulge in the mass below; the stria described by A.A. were not observed, due obviously to the time that had elapsed.

- The displacements observed subsequent to the tremors of 15th September confirmed their extreme variability.

- The rocky masses involved are exclusively more or less compacted surficial deposits; the ground cracks are interrupted at the bedrock (Mount Cuarnàn).

- Below the cracks, in certain cases, observation disclosed the bulges typical of a surficial layer moving slowly over its bedrock.

Taken together, these elements lead to interpretation of the ground cracks as detachment of debris following stresses due to the earthquake, with subsequent slow slippings downhill, both due to repetition of the tremors and simply to the effect of gravity. We therefore feel that these ground cracks, like the others recorded in the stricken area, do not represent surficial manifestations of displacement of the bedrock made active by the earthquake, even though this interpretation may be a more attractive one, and would fit in well with the focal mechanism of the earthquake assumed by Amato et al.[7].
5. BIBLIOGRAPHIC REFERENCES


Fig. 1 - Area primarily involved in the Friuli earthquake, 1976.
Shaded area: see fig. 2 and 9.

Fig. 2 - Geologic map of Monta Chiampòn and Cuarnàn (after Martinis, 1977 I & II).
1) alluvial deposits and fan; 2) slope deposits and talus cone; 3) glacial deposits; 4) Cormòns Flysch; 5) Stregna Flysch; 6) oolitic and cherty limestones; 7) Haupt Dolomite; 8) strike and dip of beds; 9) main fault; 10) overthrust; 11) line of geologic section. Shaded area: see fig. 3.
Fig. 4 - Geologic section through Mounts Chiampòn and Cuarnàn.
1) inactive carbonate talus heap; 2) talus heap with muddy matrix; 3) landslide debris heap; 4) Stregna Flysch; 5) cherty limestones; 6) Haupt Dolomite; 7) fault; 8) overthrust; 9) ground crack.

Fig. 3 - Outcrop map of the southern slope of Mount Cuarnàn.
1) active talus heap; 2) inactive carbonate talus heap; 3) talus heap with muddy matrix; 4) inactive landslide debris heap; 5) Stregna Flysch; 6) cherty limestones; 7) uncertain outcrops of cherty limestones; 8) strike and dip of beds; 9) shallow landslide; 10) landslide after the earthquake; 11) ground crack; 12) main counter slope.
Fig. 5 - Mount Cuarnàn: view of the southern slope.
A) steep slope with talus heap; B) undulate surface and counter slope with landslide debris heap; C) slope with muddy matrix talus heap.

Fig. 6 - Mount Cuarnàn: ground crack in the steep slope with talus heap. Measuring instruments show the further widening after the tremors of 15th September.
Fig. 7 - Mount Cuarnàn: ground crack in the southern side of the undulate surface. Calcitic incrustation in pre-existing fracture are visible.

Fig. 8 - Mount Cuarnan, steep slope area: ground crack with the downward side upthrown for slide of the upward side.
Fig. 9 - Geologic map of Tremugna Valley (after Martinis, 1977).  
1) alluvial deposits and fan; 2° slope deposits and talus cone; 3) Ric Tremugna sandstones and marls; 4) Peñis breccias; 5) Clauzetto Flysch; 6) Scaglia ros- sa; 7) Cretaceous limestones; 8) Jurassic limestones; 9) Haupt Dolomite; 10) strike and dip of beds; 11) main fault; 12) overthrust. Shaded area: see fig. 10.

Fig. 10 - Tremugna Valley: ground crack in the southward of the undulate surface near the counter slope. Carbonate blocks are landslide debris.
Fig. 11 - Outcrop map and geologic section between rivers Chandarar and delle Tovi. 1) landslide triggered by the earthquake; 2) active talus heap; 3) inactive talus heap; 4) landslide debris heap; 5) Rio Tremugna sandstones and marls; 6) Ellipsactinia limestone; 7) Haupt Dolomite; 8) strike and dip of beds; 9) overthrust; 10) landslide; 11) landslide scarp; 12) ground cracks; 13) upthrown side, downthrown side; 14) main counter slope; 15) line of geologic section.
SEISMOTECTONIC INVESTIGATIONS IN NORTHEASTERN ITALY

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ABSTRACT
Northeastern Italy has been the site of geomorphologic, tectonic investigations as well as of studies on its seismicity. The elaboration and the correlation of the data collected have put into evidence a well defined seismotectonic area characterized, with respect to the surrounding areas, by its historic seismicity and by its tectonic style. The tectonic structures connected with the historic earthquakes of greater intensity have, moreover, been identified within the aforesaid seismotectonic area and, outside it, the zones of more elevated propagation and attenuation of the seismic waves.

RESUME
Nous avons conduit une recherche sur la géomorphologie, la tectonique et la sismicité historique du Nord-Est de l'Italie. L'élaboration et la corrélation des données obtenues ont mis en évidence une bien définie région sismotectonique caractérisée, par rapport aux régions environnantes, par sa sismicité historique et son style tectonique. Dans la région sismotectonique on a mis aussi en évidence les structures tectoniques liées aux tremblements de terre historiques de plus grande intensité; et, au dehors de la région, les zones où la propagation et l'atténuation des ondes sismiques sont plus fortes.
FOREWORD

The seismotectonic studies have been conducted in the north-eastern area of Italy, bounded to the southeast by the well known Schio-Vicenza Tectonic Line.

For purposes of fitting the region into a seismotectonic scheme, the fundamental geostuctural characteristics given in the geologic literature have been completed by observations on its neo-tectonics. The seismotectonic considerations expressed in this study have the aim of calling to the attention the most interesting aspects with a view to the safety of nuclear installations. The main considerations are: the possible presence of seismotectonic areas - understood as being areas characterized by the relative consistency of their seismicity as well as of their geologic and structural formations; the most important seismogenic tectonic structures; the areas of highest propagation and attenuation of seismic waves.

THE GEOTECTONIC SKETCH

From a regional geomorphological point of view the areas considered may be subdivided into two large parts; the former part mountaineous and hilly including the Southern Alps, the Venetian, Carnic and Julian pre-Alps and the Gorizia-Triestine Karst; the latter part consisting of the ample plain that extends southwards of the Alpine Arc, from the foot of the pre-Alps to the Adriatic Sea (Figure 1).

For the regional and detailed geology of these two parts, reference is made to the Authors who have studied them most recently and who have placed their fundamental characteristics into evidence by means of thorough-going breakdowns /1 - 8/. In this work we have limited ourselves to citing the fundamental geostuctural characteristics reported by the Authors, that can serve to fit the region into a seismotectonic scheme.

The Southern Alps and relative pre-Alps located along the line between the Giudicarie and the Triestine Karst are divided into two areas by the Valsugana-Piave Line, characterized by different tectonic styles (Figure 1). To the NW of this area a stable non-subsident zone has persisted in time. It is known as the Alto Strutturale Atesino in which the sedimentary succession has a thickness of less than 2000 meters. The Eastern Basin, generally characterized in time by intense subsidence and by notable variations in area of the sedimentary basins forming a part of it (Belluno Basin, Carnic and Julian Basins), extends to the SE and E of the Valsugana-Piave Line. The sedimentary succession, here, has reached a thickness of many thousands of meters.

The Alto Strutturale Atesino consists of an extensive porphyric sheet resting on a schistocrystalline basement, interested by numerous magmatic intrusions which have made more rigid the same. The tectonic style with large folds and blocks dislocated with respect to one another by sub-vertical or steeply inclined faults is strictly tied to the rigid response of the basement and of the porphyric sheet to the Alpine orogenic stresses. Also the Mesozoic reefs, which in the area consist of outcroppings of limit-
Figure 1 - Main tectonic dislocations, edges of the Miocene and Quaternary sedimentary basins and the Piedmont Margin; this divides the studied area into two large geomorphologic units: to the north the Southern Alps s.s. and the pre-Alps, to the south the Venetian-Friuli Plain.
1: Overthrust and reverse fault (surface); 2: Overthrust and reverse fault (subsurface); 3: Main fault (surface); 4: Main fault (subsurface); 5: Anticlinal axis; 6: Synclinal axis; 7: Boundary of the Miocene sedimentary basin; 8: Boundary of the Quaternary sedimentary basin; 9: Piedmont Margin.
ed extension and thickness, behave as rigid masses. In the Berico-Lessinea area located to the SW of the Schio-Vicenza tectonic Line, the tectonics consist mainly of sub-vertical faults in various systems. The Valsugana Line, a tectonic structure of considerable importance, has considerably lowered the crystalline basement that represents the substratum of the Eastern Basin. This is characterized in main features by a compressive tectonic style, roughly longitudinal, consisting of folds and recumbent folds, break-thrusts and reverse faults accompanied by large overthrusts. The Eastern Basin may be subdivided into three zones the main tectonic structures of which have notable different trends: the northern, the southwestern and southeastern zones. In the northern tectonic zone (Carnic and Julian Alps and part of the Carnic pre-Alps) bounded to the north by the Gail Line and to the south by the edge of the Miocene sedimentary basin, the main tectonic structures present an essentially EW-trend. In the most eastern part of the same zone, to the east of the transversal dislocation system of a prevalently NNE-SSW orientation of the But-Chiarzo system, where carbonatic formations predominate, the tectonic style is formed partially of rigid blocks, however maintaining the general characteristics of the zone as to age and direction.

In the southwestern tectonic zone, included between the Valsugana Line and the Piedmont Margin (Venetian and Carnic pre-Alps) the tectonic structures, prevalently in the nature of folds, are oriented in a NE-SW direction. These tectonic structures, originated by compressive stresses having an approximately NW-SE direction (Cornuda), have involved also the Miocene and the lower Pleistocene sediments. And have given rise to notable differential upward movements of the zone being considered. To the NE of the Livenza River, in fact, a general stratigraphic gap during the Pliocene is noted.

In the southeastern tectonic zone (Julian pre-Alps and Karst) to the east of the Miocene and Quaternary basins, the tectonic structures of a compressive nature take on a NW-SE or dinaric direction. The structures consist of folds, break-thrusts, reverse faults and overthrusts. The tectonic stages have been active during the Pliocene and Quaternary Ages, as will be clarified later.

The longitudinal tectonic structures of the Eastern Basin outlined above have, in turn, been intersected by transversal faults; the main ones will be mentioned below.

The Schio-Vicenza Line, a dislocation of strike slip fault type, has displaced the Piedmont break-thrusts with visible horizontal throw. Similarly, in relation to the Piave River Valley between Feltre and Montebelluna, a NNW-SSE oriented fault seems to have dislocated the Piedmont break-thrusts with a horizontal displacement of several hundreds of meters. A system of transverse faults runs along the Fadalto rift and to the east of it, into the Alpago and Cansiglio.

The But-Chiarzo system of transverse faults has already been mentioned. Several other faults located between the upper Piave Valley and Val D'Aupa are oriented in a similar direction (NNE-SSW).
The fundamental tectonic lines of the Eastern Basin can be recognized also on the gravimetric Bouguer anomaly map (Figure 2). The gravimetric structures (minima, maxima, ridges, valleys), in fact, take on a NE-SW orientation between the Valsugana Line and the Piedmont Margin, an E-W orientation between the upper valley of the Piave River and the northeastern border of Italy and a NW-SE direction NE of the eastern limits of the Miocene and Quaternary sedimentary basins. In particular, the alignment of the minima just above the Piedmont Margin, between the Brenta and Tagliamento Rivers, puts the thickening of the sedimentary sheet into evidence; the Belluna 'nose' indicates the approach of the substratum to the surface and the thinning by erosion of the sedimentary sheet as a consequence of the Pliocene and Quaternary upward movements; the 'gravimetric valley' along the Piave River upstream from Feltre demonstrates the thickening of the sedimentary sheet by the action of the folding phenomena and scanty erosion. The morphologic, stratigraphic and geophysical data relative to the plain put into evidence the existence of greater downward movements of the Cretaceous limestone roof and overlying formations in proximity of the Piedmont Margin, which also largely forms the border of the Quaternary sedimentary basin (Figure 3). These downward movements were still locally present in the Upper Pleistocene and are probably still active. To the south of Udine, in fact, at Pozzuolo del Friuli, the edge of the Quaternary basin is marked by a WNW-ESE dislocation put into evidence, at a depth, by the geophysics and by the iso-anomalous lines of the Bouguer map, confirmed by the Terenzano 1 and Lavariano 1 wells of AGIP Mineraria and possible of reconstruction on the surface along the southern margin of the pre-Wurmian reliefs (Figure 4). This shift has involved thick continental deposits of age later than that of the marine Pleistocene and has perhaps influenced also the surface hydrography. For these reasons the tectonic displacement, and hence the edge of the Quaternary basin relative to it, can in all probability be considered still active today. It can also be recalled, in addition, that drillings between Venice and Grado indicate that the base of the marine Pleistocene deepens towards the NW, as does to the Cretaceous limestone roof.

Geomorphic anomalies also indicate recent deformations of the plain. The hydrographic network of the Livenza River, for example, in the plain is indicative of a paleo-surface of accumulation owing to the depression of the area included between the Piave and Tagliamento Rivers; a depression which turns out to be deeper at the Piedmont margin (Figure 5). Again, the Bouguer anomaly map, in its outlines, demonstrates a decrease in values proceeding from SE towards NW, with a gravimetric alignment of the minima along the Piedmont Margin (Figure 2). We recall, finally, that the study of images taken from the ERS1 satellite of the area under consideration has placed into evidence an alignment that crosses the plain in a NNE-SSW direction from Gemona to the Venetian lagoon, an alignment that is interpreted as a left strike-slip fault \[ \frac{\text{9}}{\text{9}} \].

The above observations, in particular the compressive tectonics and the existence of greater lowering of the Cretaceous limestone roof and of the overlying sediments in proximity of the Piedmont Margin, lowering that shows regional immersion, roughly towards the north and probably
Figure 2 - Bouguer's anomaly map.
Figure 3 - Schematic geologic section.
1: Terrigenous sediments (Quaternary); 2: Molasse (Miocene) and flysch (Eocene); 3: Limestone and dolomite (Mesozoic).
Figure 4 - Geologic sketch and section of the Puzzolo del Friuli zone.  
1: Alluvial deposit, Oligocene; 2: Alluvial and fluvioglacial deposit, late Pleistocene; 3: Fluvioglacial deposit, late Pleistocene (pre-Wurm); 4: Marine sand and clay, early Pleistocene; 5: Marl and Molasse, Miocene; 6: Marl and sandstone (flysch), Eocene; 7: Limestone, Paleocene; 8: Reverse fault; L 1: Lavariano 1 well; T 1: Terenzano 1 well.
Figure 5 - Stream system of Livenza River.
still active, indicate tectonic overtrusts of the pre-Alps towards the plain, accompanied by lowering (with undertrusts?) of the schisto-crystalline substratum in proximity of the margin of the plain due to roughly NW-SE thrusts.

CONSIDERATIONS ON THE SUBJECT OF SEISMOTECTONIC

The information furnished by the literature on the subject of seismotectonics from the eastern central Alpine Arc, as derived from a comparison between the historic seismicity on the one hand /10, 11/ and the classical tectonic scheme on the other hand, indicate that the epicenters of the earthquakes, in general, do not seem to be related (if the Gail Line and perhaps a tract in the Schio Vicenza Line are excluded) to the main tectonic dislocations (Figure 6). The epicenters, on the other hand, tend to concentrate along a strip of terrains that runs to the north of the Piedmont Margin. The Margin, representing a geomorphologic element of great relevance and constituting an important indication of Plio-quaternary tectonic deformations, bounds therefore towards the south a strip of terrain affected by seismogenic tectonic structures. In addition to the epicenters, also the trend of isoseisms of the earthquakes with a more extensive propagation seems to point out the seismogenic character of the tectonic structures that run to the north of the Piedmont Margin; this is shown in the map of Figure 7.

It has been said that, in general, it does not seem possible to relate the historic earthquakes epicenters to the principal tectonic structures. These, however, during earthquakes have sometimes a role, either as sites of renewed seismic activity or as preferred seismic wave propagation lines or, yet, as interruptions in the propagation of seismic waves (Figure 8).

As far as concerns the area being examined in the preceding pages of this study, it was put into evidence that the Eastern Basin bounded to the NW by the Valsugana-Piave Line and to the south by the Piedmont Margin, is clearly characterized from a tectonic point of view with respect to the surrounding areas. Also the seismicity characterizes the Eastern Basin. In fact, the map providing the epicenters of earthquakes of the 4th or higher degree on the MCS scale (Figure 9) demonstrates that the epicenters fall, for the most part, in the area occupied by the same Basin. The coincidence of the geotectonic area with the seismic area is evidenced better yet by the map providing the epicenters relative to quakes of the 6th degree or higher (Figure 10): almost all the epicenters fall within the area occupied by the Eastern Basin. The said area, clearly distinguished by its tectonic and seismic characteristics from the adjacent Venetian-Friuli plain and the Alto Strutturale Atesino, can therefore be considered a 'seismo-tectonic zone'.

Within this zone, the map giving the epicenters of 8th or higher degree quakes (Figure 11) demonstrates that the seisms of greatest intensity occurred for the most part along a strip of terrain lying in a SW-NE direction, between the Brenta River and the national boundary, located
Figure 6 - Main tectonic lines of the east-central Alpine arc and epicenters of historic earthquakes.

The area taken into study in this work is contained within the dotted lines.
Figure 7 - Isoseisms of the earthquake occurring on June 29, 1813.
Figure 8 - Isoseisms of the earthquake occurring on June 8, 1934. Among other things, the renewal of seismic activity along a tract of the Schio-Vicenza Tectonic Line and the preferential propagation of the seismic waves along the Valsugana-Piave and Gail Tectonic Lines, are evident.
Figure 9 - Map of the epicenters of the 4th degree and higher on the MCS scale (from 1500 to 1976).
Figure 10 - Map of the epicenters of the 6th degree and higher on the MCS scale (from 1500 to 1976).
Figure 11 - Map of the epicenters of the 8th degree and higher on the MCS scale (from 1500 to 1976).
mostly just above the Piedmont Margin. The presence of such a strip involved in the quakes of greatest intensity appears also from the forms of the areas involved in quakes of the 8th degree (Figure 12).

The existence of relationships between tectonic dislocations and seismicity becomes evident from the trend of the epicentral directions of propagation (or direction of the extension of the epicentral isoseisms, Figure 13). In the various tectonic zones of the Eastern Basin, in fact, these directions take on trends similar or equal to those of the tectonic dislocations; E-W in the northern zone, NE-SW in the southwestern zone and NW-SE in the southeast zone. In this last case the epicentral directions of propagation are, however, not exactly consistent with the tectonic directions which show WNW-ESE trends. The correlation, in general, is good also between the epicentral directions of propagation and the transversal tectonic structures.

Along general lines it can therefore be affirmed that the tectonic lines to which the epicentral propagation directions may be associated are to be considered seismogenic.

The comparison between the epicentral propagation directions and the peripheral propagation directions turns out to be particularly interesting with regard to the effects of the propagation or attenuation of the seismic waves, both in the seismotectonic area and in that adjoining it.

In the majority of cases these last coincide with tectonic structures recognized as seismogenic for their being associated during earthquakes to epicentral propagation directions. It is not rare that the seismogenic character of the tectonic structures which constitute the preferred paths of propagation are demonstrated by the occurrence along them of renewals of seismic activity. In a few cases, mainly along a strip of terrain running between Tolmezzo-Gemon and Treviso-Venice, the propagation occurs along tectonic structures not recognizable on the surface and not even through seismic reflection survey, structures that are not seismogenic because they cannot be associated to epicenters. The case of seismogenic or not tectonic displacements that constitute an obstacle to the propagation of seismic waves is also frequent. In such situations, areas in which strongly attenuated seismic waves arrive are formed: sometimes, however, the tectonic dislocations constitute an obstacle only to the propagation of seismic waves generated by very superficial earthquakes, occurring most likely in the sedimentary sheet.

On the whole the tectonic structures play a fundamental role in the control of propagation and attenuation of the seismic waves, generally with as much more evidence as the earthquakes are stronger and deeper.

Because of the importance that these phenomena assume in relation to problems concerning antiseismic plans for the area being considered in this study, it is thought to be useful to examine in detail the correlations existing between the tectonic dislocations and the directions of propagation of the seismic waves, be they epicentral or peripheral, in the various tectonic zones of the Eastern Basin.
Figure 12 - Isoseisms of the 8th degree and higher (MCS scale) of quakes occurring from 1500 to 1976; the dotted line indicates the isoseisms of the 8th degree of the earthquake of May 6, 1976.
Figure 13 - Epicentral directions of propagation of seismic waves derived from the isoseisms of earthquakes occurring from 1500 to 1976.
In the northern zone the tectonics are substantially characterized by longitudinal overthrusts of E-W direction (Comeglians-Pontebbatarvisio Line, Sauris-Zuglio Line, Forni di Sopra-Verzegnis-Resia Line and the group of lines of the 'peri-Adriatic' structure in the tract east of Barcis) and by transversal faults of NNE-SSW direction (the Upper Piave Line, the Forni di Sopra-Formi Avoltri Line, the Ampezzo-Ovario Line, the Maniago-Tramonti Line, the But-Chiarzo Line, the Osoppo-Moggio Line); the epicentral propagation directions present E-W, NNE-SE trends. Those of E-W and NNE-SSW can readily be correlated with the lines mentioned above, both longitudinally (if the group of peri-Adriatic lines that cannot be correlated with earthquakes are excluded) and transversally: among these last the But-Chiarzo has been particularly active in the area of the intersection with the E-W overthrusts. The NW-SE epicentral propagation directions are not matched by recognized surface tectonic lines, if not by those in dinaric direction present immediately to the SE, in the southeast zone; the NW-SE propagation directions of the northern zone would, therefore, induce us to suppose that they correspond in depth to the extension of the dinaric dislocations of the southeast zone.

Taking the isoseisms of the earthquakes connected with overthrusts of E-W direction into examination, it appears that the propagation of the seismic waves sometimes presents only E-W epicentral directions; other times they also show peripheral directions of different orientation. In the first case the isoseisms are close to one another and the depths of the earthquakes epicenters are very superficial, likely in the sedimentary sheet (Figure 14 A). In the second case the epicentral isoseisms are relatively far away from one another and the epicenter is situated at a greater depth than in the former case, probably in proximity of the schisto-crystalline substratum or in the uppermost part of the same (Figure 14 B).

The seismic waves of earthquakes occurring in relationship with the E-W overthrust lines go towards SW along the tectonic dislocations of the southwest zone of the Eastern Basin, towards SE along the tectonic dislocations of the southeast zone, and towards SSW along a group of lines running from Tolmezzo-Gemon to Treviso-Venice (Figure 15). Along this group of lines, as already said, tectonic dislocations are not recognized on the surface, not even by means of seismic reflection surveys, while an alignment derived from the images taken by the ERST satellite is indicated [9]. It is likely that group of lines of propagation corresponds to a deep NNE-SSW dislocation involving the schisto-crystalline substratum.

The foregoing, relative to the earthquakes associated with the E-W longitudinal dislocations of the northern tectonic zone, is substantially valid also for the peripheral propagation lines of earthquakes associated with the NNE-SSW transversal dislocation of the same zone (Figure 16). Earthquakes of distinctly higher intensity (8th - 9th degree in 1812, 9th degree in 1788 and 1928, 9th - 10th degree in 1794 and 10th in 1976) are however associated with such transversal dislocations, and have hypocentral depths reaching also the deep part of the schistose-crystalline basement.
Figure 14 - An example of isoseisms of earthquakes connected with longitudinal E-W overthrusts of the northern tectonic zone. At the top (A) progress of isoseisms of earthquake with very superficial hypocenter (earthquake of December 15, 1898). At the bottom (B) progress of isoseisms of earthquakes with deeper hypocenter and peripheral propagations (earthquake of December 12, 1924).
Figure 15 - Epicentral (solid lines) and peripheral (broken lines) directions of propagation, derived from the isoseisms of earthquakes connected with longitudinal E-W overthrusts of the northern tectonic zone.
Figure 16 - Epicentral (solid lines) and peripheral (broken lines) directions of propagation, derived from the isoseisms of earthquakes connected with transversal tectonic displacements of NNE-SSW direction of the northern tectonic zone.
As far as the epicentral direction of propagation with NW-SE trend of the northern tectonic zone is concerned, it has already been said that there seems to be a possible correlation with the displacements of dinaric direction of the southeast tectonic zone. With regard to the peripheral propagation directions (Figure 17) and to the hypocentral depth of earthquakes associated with these displacements, what has already been said about the earthquakes of the northern tectonic zone is still valid. The hypocentral depths of these earthquakes should partly be considered as very superficial and partly probably as associated with the upper part of the schistos-crystalline substratum.

The southwest tectonic zone of the Eastern Basin, bounded to NW by the Valsugana Tectonic Line and to SE by the Piedmont Margin, is characterized by prevalently plicative tectonic structures of NE-SW direction (mainly the peri-Adriatic Line between Fonzano and Barcis-Claut and a system of break-thrusts in the vicinity of the Piedmont Margin), intersected by transversal faults of NW-SE direction (principally the Piave Line between Feltre and Montebelluna and a system of faults along the Fadalto rift and to the east of the same, into the Alpago and Cansiglio).

From a seismic point of view, the tectonic zone at present under study is not bounded to NW by the Valsugana Line, but by the edge of the Miocene sedimentary basin. This, therefore, represents the limit of the seismogenic structures, similarly to the edge of the Quaternary sedimentary basin, roughly situated near the Piedmont Margin.

The epicentral directions of propagation show NE-SW and NW-SE trends and are therefore easy to correlate with the above mentioned tectonic lines, either longitudinal or transversal (Figure 13); the greater seismic activity occurs, as a rule, at the crossing of the two tectonic directions. A group of epicentral directions of NW-SE propagation, passing through Claut and Barcis, does not, however, manifest itself in known tectonic displacements. It is indicated by geomorphologic signs roughly aligned with the T. Cellina Valley.

Taking into examination the isoseisms of the earthquakes related to the prevalently plicative dislocations of NE-SW direction, in connection with the peripheral propagation of seismic waves, it is possible to observe that the propagation is practically absent north of the Miocene sedimentary basin and south of the Quaternary sedimentary basin (Figure 18). The earthquakes of greatest intensity (9th - 10th degree of 1965 and of 1873, Figure 7) have, on the other hand, produced high propagation towards Emilia and towards Lombardy, as well as along the eastern edge of the Quaternary sedimentary basin.

Taking into consideration the isoseisms of the earthquakes connected with the transversal tectonic dislocations of NW-SE direction, in connection with the propagation of seismic waves, it is possible to observe that these epicenters are substantially contained between the borders of the Miocene and Quaternary sedimentary basins (Figure 19). The peripheral propagations are again practically absent north of the Miocene sedimentary
Figure 17 - Epicentral (solid lines) and peripheral (broken lines) directions of propagation, derived from the isoseisms of earthquakes connected with NW-SE displacements of the northern and southeastern tectonic zones.
Figure 18 - Epicentral (solid lines) and peripheral (broken lines) directions of propagation, derived from the isoseisms of earthquakes connected with NE-SW longitudinal tectonic displacements of the southwestern tectonic zone.
Figure 19 - Epicentral (solid lines) and peripheral (broken lines) directions of propagation, derived from the isoseisms of earthquakes connected with the NW-SE transversal faults of the southwestern tectonic zone.
basin; to the south of the Quaternary basin on the other hand, they are
directed southeastwards. Propagations towards the west, towards the
Garda Lake, and of NW-SE direction in the Berico-Lessinea zone were
also observed. The earthquakes of greatest intensity (8th degree in 1836
and 9th degree in 1936) propagated preferentially towards the Po plains.

In relation to the hypocentral depths of the southwest tectonic
zone, bearing the aforesaid in mind, it turns out that the greatest depths
are associated with the NE-SW tectonic displacements. It is to be noted,
moreover, that taking the isoseisms of the earthquakes of greatest
intensity and greatest extension into consideration (earthquakes of the
years 365, 1117, 1873) it appears evident that they are to be related to
the important tectonic structures situated close to the Piedmont Margin
and extending from Gemona as far as Piedmont.

CONCLUSIONS

In summary it turns out that:

a) A migration of tectonic movements has occurred, along general lines,
from north to south; for example, taking the southwest tectonic zone
into examination, the tectonic activity has shifted from the Valsugana
Line, today practically without activity, to the edges of the Eocene and
Miocene basins. They bound towards NW the seismic area. At present
the tectonic movements reach the Piedmont Margin which marks the
limits to SE of the seismic area and which corresponds to the edge of
the Quaternary sedimentary basin.

b) The existence of a well defined 'seismotectonic area' characterized by
a relative consistency of its seismicity and its tectonic style.

c) The most important seismogenic tectonic structures, referrable to
historic earthquakes of greatest intensity (8th degree and higher), may
be found in a strip included in the aforesaid seismotectonic area and
are located for the greatest part close to the Piedmont Margin.

d) To the south of the seismotectonic area there exists a strip of prefer-
ential peripheral seismic wave propagation, primarily generated by
earthquakes occurring in the northern tectonic zone: the strip lies
in a direction going from Maiano-Travesio (to NE) towards Venice-Tre-
viso (to SW).

e) The Alto Strutturale Atesino area and the coastal strip between Venice
and Grado are practically aseismic; the earthquakes occurring in the
seismotectonic area are here recorded in a moderate degree.
REFERENCES


SESSION I.b: GEOTECTONIC, GEOPHYSICAL AND SEISMOLOGICAL ASPECTS:
GEOPHYSICS AND SEISMOLOGY

Chairman: E. Peterschmitt
Scientific Secretary: P. Mechler
Macroseismic observations of the FRIULI earthquake of May 6, 1976

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Institut für Meteorologie und Geophysik, Universität Wien, Austria

ABSTRACT
The macroseismic data of the FRIULI earthquake taken from the Austrian territory are discussed. These data, compiled by the Zentralanstalt für Meteorologie und Geodynamik, VIENNA, have been represented as isomals which show a considerable deviation from the shape of a concentric circle. These deviations allow some worthwhile conclusions about the parameters of the focus and the local transmission function of seismic energy. The influence of the epicentral distance has been removed from the local intensity by use of the formula

\[ \delta I = I_{\text{obs}} - I_{\text{av}}(\Delta, \varphi) \]

\[ \Delta = \text{epicentral distance} \]

\[ \varphi = \text{azimuth} \]

where \( I_{\text{av}} \) means the best fitting averaged intensity at the epicentral distance \( \Delta \) and the azimuth \( \varphi \). Maps of \( \delta I \) represent the conditions of the local geological underground and yield insights into the problems of seismic risk of the area concerned. The areas of the Inn, Salzach and Drau valley have a relatively high \( \delta I \). This is a consequence of unconsolidated sediments of minor thicknesses. In contrast to this the Bohemian massiv is an area with undemoral \( \delta I \) due to the granite underground. The results agree with those taken different local earthquakes in Austria.

RESUME
Les données macrosismiques du tremblement de terre du Frioul obtenues sur le territoire autrichien ont été analysées en détail. Ces données, réunies par le Zentralanstalt für Meteorologie und Geodynamik, Vienna, ont été représentées sous forme d'isomals qui montrent une remarquable déviation de la forme d'un cercle concentrique. Ces déviations permettent de déduire quelques utiles conclusions quant aux paramètres du foyer et la fonction locale de transmission de l'énergie sismique. L'influence de la distance de l'épicentre a été éliminée de l'intensité locale au moyen de la formule suivante

\[ \delta I = I_{\text{obs}} - I_{\text{av}}(\Delta, \varphi) \]

\[ \Delta = \text{distance de l'épicentre} \]

\[ \varphi = \text{azimuth} \]

où \( I_{\text{av}} \) représente la valeur la mieux approximée de l'intensité moyenne à la distance \( \Delta \) de l'épicentre et à l'azimuth \( \varphi \). Des mappes de \( \delta I \)
représentent les conditions du sous-sol local géologique et donnent des renseignements quant aux problèmes du risque sismique de la zone en objet. Les régions de l’Inn, du Salzach et de la vallée du Drau présentent une valeur relativement élevée de σI. C’est là une conséquence de sédiments non consolidés d’épaisseur plus faible. Par opposition à celle situation le massif Bohémien est une région qui présente des valeurs de σI en-dessous du normal, à cause de la présence de granit dans le sous-sol. Les résultats concordent avec ceux obtenus de différents tremblements de terre locaux en Autriche.
The aim of this study is to establish an empirical formula as an approximation of the expected earthquake intensity at any place in Austria if the earthquake occurs in the south-eastern Alps, i.e., North Italy, North Yugoslavia or Carinthia. An important general problem is attacked herewith which includes questions of public interest such as the earthquake risk of atomic plant and the earth sciences as well.

The FRIULI shock of May 6, 1976 caused some minor destructions in Carinthia. It was felt throughout Austria with intensities between 4.5° and 7.5°MS. Therefore this earthquake is suited to serve as a model of a group of earthquakes in the same area. Actually the Friuli earthquake exhibits an anomalous extension of the shattered area to the northwest. This anomaly is found in all east alpine earthquakes. It was first described by E. SUESS (1873). The formula used in this study therefore must take into account not only the influence of the epicentral distance but also the azimuth on the local intensity.

The occurrence of the anomaly mentioned above can have two main causes. On the one hand the radiation pattern of the focus and its shape may produce a non-circular distribution of the intensity. This effect should dominate in small epicentral distances and also play a role at greater distances. On the other hand it is possible that the anomaly is caused by local variations of the physical parameters of the wave guide such as extinction, scattering of seismic energy at obstacles and the effects of guided waves. If the first of these two reasons dominates the solution of the wave equation leads to a formula like \( I \sim \ln\left(\frac{\xi}{r}\right) \) and therefore an approximation

\[
(1) \quad I_i = I_o + D - A \ln \Delta i + B \phi_i + \Theta \phi_i^2 + \Sigma \eta_i \quad i = 1, 2, \ldots N
\]

seems to be reasonable.
\[ I_i = \text{intensity of the locality } i \]
\[ I_o = \text{maximum intensity} \]
\[ \Delta_i = \text{epicentral distance} \]
\[ \varphi_i = \text{azimuth} \]
\[ \delta I_i = \text{relative intensity} \]

In the second case

(2) \[ I_i = I_o + D - (A + B \varphi_i + C \varphi_i^2) \ln \Delta_i + \delta I_i \quad i = 1, 2, \ldots, N \]

should be preferred. In order to find out which of these two equations fit the data better, a computation of the standard error of both has been carried out. The data have been taken from V.KARNIK, D.PROCHASKOVA, Z.SCHENKOVA, L.RUFRECHTOVA, A.DUDEKI, J.DRITTMEL, E.SCHMEDES, G.LYDECKER, J.P.ROTHE, B.GUTERCH, H.LEWANDOVSKA, D.MAYER-ROSA, D.CWIJANOVIC, V.KUK, F.GIORGETTI, G.GRÜNTHAL and E.HURTIG (1977) for values of \(-90^\circ \leq \varphi_i \leq 90^\circ\) only.

It turned out that the standard error of the approximation (1) is .51°MS and that of (2) is .50°MS. From this it can be deduced that both effects are of importance, but the second one exceeds the first one by a small degree. \(\delta I_i\) taken from equation (2) has been plotted and is represented in figure 1. For comparison a map of the main geological units is presented in figure 2. Figure 1 shows that the regional trend has not been reduced completely. This follows from the collection of data for equation (2) given by V.KARNIK et al. which includes the complete shattered area north of Fiuli of which Austria covers only a small part. A better suppression of the regional trend has been obtained by using the Austrian data only, given by the ZENTRALANSTALT FÜR METEOROLOGIE UND GEODYNAMIK (1976). In this case the least square fit for \(\delta I_i\) yielded

\[ A = 1.416 \]
\[ B = 0.001669 \quad [\text{degree}^{-1}] \]
\[ C = 0.000025 \quad [\text{degree}^{-2}] \]
\[ D = 1.907 \]

with \(I_o = 10^0\,\text{MS}\)
Relative intensity \( \delta I_i \) in Austria

\( \delta I_i \) taken from eqs. (2) and (3) has been plotted as can be seen in figure 3. In this figure the influence of the epicentral distance as well as an effect of azimuth with its maximum at \( \varphi_{\text{max}} = -33^\circ \) is reduced. It is expected that \( \delta I_i \) represents a measure of the local intensity which is mainly caused by the local underground. Considerations about the reliability of macroseismic data as used here are of course necessary but they are beyond the scope of this paper. The presentation of the \( \delta I_i \)-map holds for the Friuli earthquake. But it is presumed that it holds for all earthquakes in the same area. It is a striking feature that the isomals of \( \delta I_i \) mostly disagree with the main geological units. The anomaly west of INNSBRUCK, for example, covers the central crystalline of the TAUERN, the INN-valley and the northern calcareous Alps as well. From the stand point of geology no easy explanation for this anomaly can be given. Presumably the reason must be sought in the deeper structures of the alpine body. It should be emphasized that a similar anomaly occurs in connection with most of the local earthquakes near the INN-valley, as that of NAMLOS, October 8, 1930 (A.FRANKE and R.GUTDEUTSCH, 1973). South of this region an area with negative \( \delta I_i \) follows which covers different geological units as well. A correlation of high \( \delta I_i \) with the INN-valley is evident.

A positive \( \delta I_i \)-anomaly at about 14° 20' E, 46° 40' N may be explained by the dominating influence of focal parameters as this area is close to the epicenter. If this is true the anomaly has nothing to do with the local underground. It will not be discussed here.

In contrast to this feature the positive \( \delta I_i \) at 15° 40' E, 46° 50' N and the minimum north of this has surely something to do with the geological underground. This anomaly has been represented in many local earthquakes e. g. that of OBDACH, October 3, 1936 (J. DRIMMEL, G.GANGL, R.GUTDEUTSCH, M.KOENIG and E.TRAPP; 1973). The maximum can be readily explained by the alluvial sediments of minor thickness in the MUR-valley. This seems to be a contradiction of the fact that the minimum north of this area coincide with an area with alluvial sediments also. Nothing is known so far about the local thickness of these sediments. May be a resonance effect, dependent on the ratio wave length/layer-thickness would explain this anomaly.
The northern calcareous Alps and the eastern BOHEMIAN crystalline (15°E, 49°N) represent zones of low $\delta I$ in contrast to the northern foreland of the Alps with comparable high $\delta I$. This peculiarity has been interpreted as a consequence of a shadow effect (DRIMMEL et al., 1973). The calcareous Alps with a high acoustic impedance form a wedge, which overlies the FLYSCH and MOLASSE with low acoustic impedance. Therefore the main part of the seismic energy underruns the calcareous Alps and reaches the earth's surface in the north foreland. This mechanism explains the low $\delta I$ in the BOHEMIAN crystalline as well as in the calcareous Alps. It cannot explain why the western part of the BOHEMIAN crystalline (west of 14°50' E) has positive $\delta I$. An interpretation as a residual of the regional trend can be refuted as the anomaly occurs in connection with all great Austrian earthquakes (DRIMMEL et al. 1973). Apparently the geological fault "DIENDORFER STÖRUNG" represents a clear boundary between high intensities in the south east and low intensities in the north west.

For practical reasons it might be worthwhile to give the local $\delta I$ averaged over the areas in discussion

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<tbody>
<tr>
<td>Bohemian crystalline</td>
<td>- 0.3</td>
</tr>
<tr>
<td>Alpine foreland, north</td>
<td>+ 0.4</td>
</tr>
<tr>
<td>northern calcareous Alps</td>
<td>- 0.2</td>
</tr>
</tbody>
</table>

The significance of these values can be deduced from the histograms in figure 4.

A comparison with the $\delta I$-map taken from the Austrian earthquake in SEEKENSTEN April 16, 1972

As mentioned above many of the anomalies of $\delta I$ in figure 3 can also be found in the isomales of Austrian earthquakes. This fact encourages us to apply the method used in this paper to a great Austrian earthquake with an epicenter far away from Friuli. Therefore one may expect that the integral effect of extinction along the wave path is very different from that of the Friuli earthquake. A comparison can prove whether the local conditions of the underground or the integral conditions along the wave path play the more significant role. As an
example the great earthquake of SEEKENSTEIN, April 16, 1972, $I_o = 7.5^\circ$MS has been chosen as many data of this event are available (JAHRBUCH DER ZENTRALANSTALT FÜR METEOROLOGIE UND GEODYNAMIK 1972, J.DRIMMEL and G.DUMA 1974). A part of the $\Delta I$-map is represented in figure 5 using the best fitting parameters:

$$A = 0.6895$$
$$B = 0.000336 \ [\text{degree}^{-1}]$$
$$C = 0.000027 \ [\text{degree}^{-2}]$$
$$D = 0.3743$$

with $I_o = 7.5^\circ$ MS

It covers the north part of Austria and the boundary to Czechoslovakia and can be compared with the $\Delta I$-map taken from the Friuli earthquake. The agreement is striking where the signatures of the anomalies are concerned. This fact proves the assumption, that $\Delta I$ is influenced mainly by the local underground and less by the integral wave path from the hypocenter to the point of observation. It must be emphasized that the absolute values of $\Delta I$ do not agree so well. The possible reasons for that disagreement cannot be discussed in this paper. Please refer to the differences in the parameters in equ. (3) and (4), which show, that these parameters depend not only on the epicenter but also on the intensity of the earthquake.

**Literature**


JAHNPBUCH DER ZENTRALANSTALT FÜR METEOROLOGIE UND GEODYNAMIK , Wien, 1972


Zentralanstalt für Meteorologie und Geodynamik, Wien, geophysical department, personal communications, 1977
HISTOGRAMS OF δ1

BOHEMIAN CRISTALLINE

FORELAND NORTH

NORTHERN CALCAREOUS ALPS

FIGURE 4
Relative intensity $\delta I$
(regional trend reduced)

--- Friuli May 6 1976

--- Seebenstein April 16 1972 X epicenter
Contribution to the near field study of the aftershocks of the earthquakes on May 6th and September 15th 1976 in Friuli (Italy)

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H. HAESSLER *
P. HOANG TRONG *

* E.R. 181 C.N.R.S.
Institut de Physique du Globe, Strasbourg, France

ABSTRACT
The two 1976 destructive earthquakes in Friuli have been followed by a long and rich series of aftershocks. The recording of these aftershocks by a network of telemetered stations, settled in the epicentral zone, has given about 4000 earthquakes with a magnitude between 1.5 and 5.0.

The spatial distribution of the focus indicates a northern migration from May to the autumn 1976 and a concentration on a rather restricted zone around the epicenter of the two major earthquakes. The depth of the focus, between 1 and 7 km, is still superficial, even for aftershocks with a magnitude above 4.0.

The study of some focal mechanisms shows that most of the aftershocks are due to thrust motions except a few strike slip west of Tagliamento river.

We have undertaken a study of forerunning signs on the aftershocks series of September 15 earthquake. The analysis of the $V/H$ ratio shows significant variations before the main aftershocks of $M_0^{p}4.8$. This is an encouraging result with a view to the prediction of Friuli earthquakes.

RESUME
Les deux séismes destructeurs survenus au Frioul en 1976 ont été suivis par une longue série de répliques. L'implantation d'un réseau de stations sismologiques dans la zone épizentrale a permis l'enregistrement de près de 4000 secousses de magnitude comprise entre 1,5 et 5,0.

La distribution spatiale des foyers indique pour ceux-ci une migration vers le Nord entre mai et septembre 1976 ainsi qu'une concentration sur une zone relativement réduite autour des deux séismes majeurs. La profondeur des foyers comprise entre 1 et 7 km est toujours superficielle même pour des séismes de magnitude supérieure à 4.

L'étude de quelques mécanismes focaux montre que la plupart des répliques sont dues à des mouvements de chevauchement excepté quelques décrochements à l'Ouest du Tagliamento.
Nous avons entrepris l'étude des signes précurseurs pour la série des répliques au séisme du 15 septembre. L'analyse du rapport \( \frac{V_p}{V_s} \) indique des variations significatives avant les principales répliques de magnitude supérieure à 4. Il s'agit là d'un résultat encourageant du point de vue de la prédiction des séismes du Frioul.
Introduction


La tectonique des plaques suggère un chevauchement du bloc adriatique sous le bloc Europe, et fournirait selon certains auteurs (G. Müller, 1976) une explication tectonique vraisemblable aux séismes du Frioul.

Le Frioul est certainement une région fréquemment touchée par des séismes importants ou catastrophiques. Schneider (1968) cite 17 séismes destructeurs depuis l'an 1000, et les cartes des intensités maximum de Karnik (1966) montrent que la zone épizentrale de 1976 est sur l'alignement étroit qui s'étend de Vérone en Italie jusqu'à Vienne en Autriche.

La rapidité d'intervention est un gage sûr de réussite dans l'étude des séquences de répliques. Ainsi 80 heures après le séisme du 6 mai 1976 à 20h., le réseau télémétré de 7 stations était opérationnel sur la zone épizentrale. L'implantation des stations et la géométrie du réseau sont la conséquence directe des difficultés de déplacement que nous avons rencontrées dans la zone de dégâts maximum. Durant les 4 jours d'observations du 10 au 14 mai 1976, 1200 séismes ont été localisés et plus de 3700 enregistrés. Cette séquence de répliques constitue la série de données n° 1.

## Tableau des observations

<table>
<thead>
<tr>
<th>Séisme principal</th>
<th>Période d'observations</th>
<th>Résultats</th>
</tr>
</thead>
<tbody>
<tr>
<td>Détectritions du</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C.S.E.M.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 Mai 1976 à 20h.00</td>
<td>du 10 Mai 1976</td>
<td>1200 séismes localisés</td>
</tr>
<tr>
<td>M = 6,5</td>
<td>au 14 Mai 1976</td>
<td>0,0 ≤ M ≤ 5,0</td>
</tr>
<tr>
<td>46.23°N 13.20°E</td>
<td>durée : 4 jours</td>
<td></td>
</tr>
<tr>
<td>h = 7 km</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 Septembre 1976-09h.21</td>
<td>du 29 Septembre 1976</td>
<td>plus de 3000 séismes enregistrés</td>
</tr>
<tr>
<td>M = 6,3</td>
<td>au 4 Juillet 1977</td>
<td>(étude non terminée)</td>
</tr>
<tr>
<td>46.30°N 13.18°E</td>
<td>durée : 9 mois</td>
<td></td>
</tr>
<tr>
<td>h = 11 km</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

La figure 1 donne l'implantation des stations sismologiques et une esquisse géologique.

### Détermination des foyers

Nous utilisons un programme de calcul dérivé de HYPO 71 (Eaton, 1972) et mis au point par Rodriguez (1975). Pour les séismes du Frioul, vu l'énorme quantité de séismes à dépouiller (4000) et vu la difficulté de lecture précise et rapide des ondes S, nous n'utilisons que le temps d'arrivée des ondes P. Le modèle de structure choisi est alors déterminant pour l'exactitude des localisations des foyers, en particulier pour la profondeur et le temps origine. Le problème essentiel consiste donc à choisir un modèle de croûte qui soit aussi proche que possible de la réalité géologique et en accord avec les données géophysiques existantes. Les résidus des temps de parcours devront être faibles.

Les données de la prospection en sismique réflexion nous fournissent quelques renseignements sur la vitesse des couches superficielles (Muezzin, 1976). Quatre sondages sismiques, intéressant surtout la partie Sud de la zone épincérale, sont disponibles. Sur ces 4 sondages, l'un est localisé au Sud de la faille de Tricesimo, un deuxième est situé sur cette faille, les deux autres sont entre Osoppo et Gemona. V<sub>P</sub> moyen croît du Sud vers le Nord. Alors qu'au Sud de la faille, la valeur V<sub>P</sub> moyenne = 3,5 km/sec est atteinte pour une profondeur de 2,5 km, dans la région de Gemona cette vitesse est atteinte dès 1 km. Pour les couches plus profondes nous adopterons la vitesse V<sub>P</sub> = 6,2 km/sec qui est déduite des grands profils sismiques.
alpins; c'est une extrapolation, faute de données concrètes.

Ces données géophysiques et géologiques nous ont servi de base dans le choix du modèle. Le reste a été affaire de tâtonnements pour obtenir les meilleures déterminations possibles en prenant comme critère les résidus 0–C minimum. Nous avons finalement été conduits à adopter deux modèles différents pour chacune des deux séquences. Ces modèles figurent sur les coupes profondeurs. Le fait que le même modèle ne pouvait être appliqué aux 2 séquences méritait des investigations supplémentaires. Pour ce faire nous avons utilisé un programme d'inversion qui permet d'obtenir une vitesse moyenne valable pour la croûte sous les stations.

Le principe de la méthode consiste en une approximation par itération de la vitesse $V_p$ au même titre que les coordonnées $X$, $Y$, $Z$ du foyer et le temps origine $T_o$ du séisme.

L'équation de base pour la station $k$ s'écrit :

$$t_k - t_o = \frac{1}{V} \left[ (x - x_k)^2 + (y - y_k)^2 + (z - z_k)^2 \right]^{1/2}$$

Si nous désignons par $(x', y', z', t'_o, v')$ une solution approchée, un développement au 1er ordre conduit à la relation

$$F = t_k - t'_o - \frac{D'}{V} - \Delta t_o - \frac{\Delta x}{V_D}, (x' - x_k) \ldots$$

avec $D' = \left[ (x' - x_k)^2 + (y' - y_k)^2 + (z' - z_k)^2 \right]^{1/2}$ distance hypocentrale approchée.

On résout $F = 0$ au sens des moindres carrés pour les inconnues $\Delta x$, $\Delta y$, $\Delta z$, $\Delta t_o$ et $\Delta v$. L'ensemble des 7 stations est pris en compte pour un choix de 10 séismes. D'où 70 équations pour 41 inconnues. Le résultat obtenu servira de base à l'itération suivante - arrêt des itérations lorsque les résidus $(t_k - t'_o) - \frac{D'}{V}$ sont inférieurs à 0.005 secondes.

Les résultats obtenus par cette méthode montrent que les vitesses moyennes $V_p$ que nous devons adopter ne sont pas les mêmes pour les périodes I et II.

Pour les 4 jours d'observations de mai 1976, nous obtenons

$$V_p = 5,0 \pm 0,3 \text{ km/sec}$$

Pour la longue série n° II nous obtenons

$$V_p = 6,2 \pm 0,1 \text{ km/sec}$$

Une autre méthode confirme ce résultat:
Une même série de séismes est calculée à l'aide du programme HYPO 71 pour différentes vitesses moyennes $V_p$. Les figures (2, 3) donnent les résidus $0-C$ pour les deux périodes en fonction de $V_p$ adopté. Nous observons que pour la période I le résidu moyen ne passe pas par un minimum mais reste très constant ($\approx 0.06$ sec) et les résidus aux différentes stations sont toujours importants. Pour la période II nous observons très nettement que la valeur $V_p$ moyen = 6,2 est la mieux adaptée. Cette valeur est conforme à l'extrapolation des résultats des grands profils alpins. Nous retrouvons donc par deux méthodes différentes le contraste de vitesses entre les périodes I et II et notre premier choix de modèle est confirmé. Nous l'avons donc maintenu, mais l'expérience nous a montré que ces modèles à couche peuvent facilement se réduire ici à des demi-espaces homogènes dont les vitesses moyennes sont celles définies ci-dessus.

La valeur $V_p$ moyen faible pour la séquence I est sans doute due à la proximité dans le temps du séisme majeur, elle est certainement limitée dans l'espace à la zone focale.

Etude critique des résultats

L'heure origine $T_o$ déduite des droites de Wadati peut être considérée comme exacte, en effet elle est indépendante de la connaissance préalable de l'hypocentre et de la loi des vitesses des ondes P et S.

Si $T_c$ désigne l'heure origine calculée à partir des seules arrivées de l'onde P, nous pouvons utiliser le résidu $T_o - T_c$ comme un test de validité du modèle choisi (fig. 4). Pour un millier de séismes nous obtenons une valeur moyenne de $(T_o - T_c)$ de $-0.15$ sec. Le résidu $T_o - T_c$ semble être fonction de la profondeur des foyers, notre modèle est mieux adapté aux cinq premiers kilomètres où la moyenne de $(T_o - T_c)$ n'est que de $-0.05$ sec.

Indépendamment du modèle de croûte choisi, la précision des déterminations est surtout fonction des positions relatives des stations et des foyers. A l'intérieur du polygone des stations les foyers sont déterminés avec un écart type inférieur à 250 m sur les coordonnées et inférieur à 0.1 sec sur le temps origine. La profondeur n'est obtenue avec précision que si les distances épico-centrales sont assez variées et de l'ordre de grandeur de cette profondeur. A l'extérieur les erreurs sont fortement dépendantes de la distance du foyer au réseau, ces erreurs peuvent dépasser 2 km pour des séismes à quelques 10 km du réseau.
Pour la période II la géométrie du réseau était assez bien adaptée à l'étude des répliques, par contre le dispositif mis en place lors de la séquence I manquait un peu d'ouverture. Lorsque l'on fait varier quelque peu le modèle de croûte, la détermination en X et Y varie très peu si les séismes sont à l'intérieur du réseau. Par contre la profondeur et le temps origine y sont très sensibles.

Le modèle de croûte adopté pour la période I n'est pas pleinement satisfaisant, en effet les résidus des temps de parcours restent souvent importants. Les premiers résultats de l'application de la méthode d'inversion tridimensionnelle de Aki indiquent d'ailleurs de fortes hétérogénéités latérales pour cette période. Pour la période II le modèle choisi semble correspondre à la réalité.

Remarquons que la difficulté majeure habituellement rencontrée dans le travail des déterminations est l'imprécision des lectures des temps d'arrivée. Cette imprécision a généralement pour cause le défilement trop lent du papier et une connaissance souvent inexacte ou insuffisante des différentes corrections de temps. Ces deux difficultés sont inexistantes avec le type d'instrumentation dont nous disposons. Les limites de la détermination sont repoussées. Le modèle de croûte adopté devient alors prépondérant.

Cartes de séismicité

La figure 5 regroupe les résultats des détermination des deux périodes d'observations. La zone de répliques de la séquence I est nettement limitée vers le Sud et l'Ouest, son extension est par contre plus diffuse vers le Nord et l'Est. La petite concentration des foyers vers le Sud-Ouest sur la rive droite du Tagliamento est constituée essentiellement par le séisme de magnitude 5.0 du 11 mai à 23h.45 et par ses répliques. Le phénomène est bien limité dans le temps et localisé sur une zone très faillée. La coupe Nord-Sud de la séquence n° 1 (fig. 6 ) renforce encore l'image du fort groupement, les profondeurs s'étant entre 2,5 et 6 km.

Les surfaces définies par les isosismes IX$^{1/2}$ et IX du séisme majeur du 6 mai (D. Mayer-Rosa, 1976), retracés sur la figure 7, et la surface définie par la forte concentration des épicentres sont assez concordantes. Les isosismes semblent plus rapprochées vers le Sud et plus espacées dans les autres directions. Ce fait peut être mis en relation, sans en fournir une explication avec la limite très nette de la zone des répliques vers le Sud.

La zone des répliques observées pendant la séquence n° 2 (fig. 8) présente toujours une limite assez nette vers le Sud. Cette zone est déplacée
de 5 km vers le Nord par rapport à celle de la séquence de Mai. Ce déplacement correspond d'ailleurs au déplacement relatif des foyers des 2 séismes majeurs tels qu'ils sont donnés par le C.S.E.M. La concentration des épicentres indique des alignements de tendance générale Est-Ouest selon la direction des grandes failles de chevauchement. Remarquons que des groupements, de direction Nord-Sud apparaissent aussi, en particulier le long des vallées du Tagliamento et du Lago Cavazzo vers Tolmezzo. C'est le long de ces derniers alignements que nous avons trouvé des mécanismes focaux du type "strike-slip". La forte densité d'épicentres semble se concentrer à la jonction des failles de chevauchement et des failles transcourantes.

La figure 9 regroupe en coupe verticale Nord-Sud les séismes bien déterminés de $M \geq 2,5$ pour les deux périodes d'observations. Cette coupe fait ressortir, plus précisément pour la séquence n° 1, que les répliques même les plus fortes sont assez superficielles. Les séismes les plus forts de la série n° 2 s'étagent par contre depuis la surface jusque vers 15 km de profondeur. Un alignement des foyers selon un plongement vers le Nord apparaît très nettement suivant un pendage moyen de 40° environ. Le mécanisme focal composite fait à partir des séismes de $M \geq 2,5$ localisés sur ce plongement, donne pour l'une des solutions possible: une faille de chevauchement d'azimut Est-Ouest et dont le pendage est précisément de 40° vers le Nord. Ce fait confirme la prédominance des mouvements de chevauchement pour les répliques des séismes du Frioul (Fig.10).

La relation empirique $M = \log_{10} A + 3,7$ de UTSU liant la magnitude $M$ du séisme principal à la surface $A$ en kilomètres carrés de la zone de répliques nous conduit à une magnitude 6,2 pour le séisme du 15 Septembre 1976 en estimant la surface A à 340 km$^2$. La relation équivalente de Bath-Duda $M = 0,68 \log_{10} V - 6,52$ relie le volume $V$ (km$^3$) de la zone de répliques à la magnitude. Nous estimons ce volume à 5100 km$^3$, la magnitude est alors de 6,2 toujours pour le séisme du 15 Septembre 1976. Ces deux résultats sont identiques et assez vraisemblables. La séquence n° 1 ne permet pas de telles évaluations car la durée d'observations était notablement trop courte.

Variation du rapport $V_p/V_s$ pour les séismes du Frioul.

Certains auteurs pensent que le phénomène de dilatance n'apparaît que dans les régions de failles de chevauchement; c'est le cas du Frioul où les failles de chevauchement sont largement prédominantes. Il semble donc intéressant de tenter une étude des variations temporelles du rapport $V_p/V_s$ sur les séries des répliques au séisme du 15 Septembre 1976.
L'étude porte sur une période allant du 30 septembre 1976 au 16 Décembre 1976, elle comporte plus de 1000 séismes de magnitude supérieure à 1,5 (G. Wittlinger et al, 1977). A partir des droites de Wadati construites d'après les dépouillements des séismogrammes nous tiron les valeurs moyennes journalières du rapport \( V_p / V_s \) (fig. 11, 12). Les valeurs moyennes présentent encore des fluctuations importantes. Nous en voyons deux explications possibles:

a) Les séismes de magnitude plus grande que 3.0 qui sont probablement précédés d'une phase dilatante sont très nombreux pendant notre période d'observations. La phase dilatante d'un séisme, caractérisée par la diminution de \( V_p / V_s \) peut très bien recouvrir la phase diffusive d'un autre séisme. Le fait apparaît sur la fig. 12 où par exemple le séisme de \( M = 3.7 \) du 13 Novembre 1976 précède de 10 jours le séisme de \( M = 4.2 \) du 23 Novembre 1976. Nous schématisons ce phénomène sur la figure 13.

b) La variation spatiale du rapport \( V_p / V_s \) apparaît sur les diagrammes de Wadati (fig. 11). Ces variations sont sans doute dues à l'hétérogénéité de la région.

Malgré ces difficultés, nous avons mis en évidence des variations temporelles de \( V_p / V_s \) avant des séismes importants. C'est un résultat qui semble encourageant pour l'étude des signes précursseurs aux séismes du Frioul. Une investigation systématique dans ce domaine devrait permettre d'aboutir à des conclusions plus sûres.
fig. 1
Fig. 9

Fig. 9a

Coupe Nord-Sud, Octobre 1976 - Avril 1977
Fig. 10a - Montage sous la forme de diagrammes de Wadati d'un séisme du 13 mai

Fig. 11 - Quatre exemples de droites de Wadati construites d'après les dépouillements des séismogrammes. La pente des droites est égale à $\frac{V_p}{V_s} - 1$
Fig. 12 - Suite temporelle des moyennes journalières $V_p/V_s$. Les flèches marquent l'apparition de séismes de magnitude $>3,0$.

Fig. 13 - Composition théorique (●) de la variation temporelle du rapport $V_p/V_s$ pour deux périodes de dilatance-diffusion, relatives à des séismes de magnitude 3,7 (○) et 4,2 (□). Ces séismes sont séparés par un intervalle de temps de 10 jours. La forme des courbes de variation de $V_p/V_s$ est choisie d'après un exemple typique de Aggarwal. Cette figure schématisse les traits majeurs des périodes a et b de la figure 12.

SEISMICITY OF THE FRIULI AREA RECORDED BY A FRENCH SEISMIC NETWORK
FROM MAY TO OCTOBER 1976

by

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ABSTRACT

The stations of the permanent seismic network of the CEA are between 500 km (South-East stations) to 1 100 km (North-West stations) from the Friuli area. The aperture is about 80°.

It has however been possible to observe a significant part of the seismicity which happened in this region between May and October 1976.

The location of major earthquakes and evaluation of the magnitude $M_L$ in each case are given, and also of certain aftershocks.

Frequencies - magnitude distributions for the two major shocks and their after-shocks are presented, the number of the latter being limited by the detection threshold of about a magnitude $M_L = 2,5$. Some 354 events recorded by this network give the following results:

\[ 3,5 < M_L < 4,5 \]  \quad \log n(M_L) = 7,09 - 1,38 M_L

\[ 5,5 < M_L < 6,5 \]  \quad \log n(M_L) = 5,81 - 0,89 M_L

These results will be discussed.

Finally, a comparison will be made between seismic activity versus time computation for the first and second earthquakes series.
RESUME

Les stations du réseau sismique permanent du C.E.A. sont situées entre 500 km (stations au sud-est du réseau) et 100 km (stations au nord-ouest du réseau) de la région du FRIOLE. L'ouverture du réseau est d'environ 80° vers la zone d'épicentres considérée.

Il a été néanmoins possible d'enregistrer une part significative des séismes entre Mai et Septembre 1976.

La localisation des séismes les plus importants ainsi que l'évaluation de leur magnitude ML est présentée.

La distribution fréquences-magnitude pour les 2 chocs principaux et leurs répliques sont étudiées, au dessus d'un seuil de magnitude de l'ordre de ML = 2,5 qui représente pour cette région, la limite de détection du réseau.

Ainsi 354 événements pris en compte donnent les résultats suivants:

- pour $3,3 < ML < 4,5$
  \[ \log n (ML) = 7,09 - 1,38 ML \]
- $5,5 < ML < 6,5$
  \[ \log n (ML) = 5,81 - 0,89 ML \]

Ces résultats sont discutés.

Enfin une comparaison de l'évolution de l'activité sismique en fonction du temps pour les deux séries de répliques (MAI/JUIN et SEPTEMBRE/OCTOBRE) est présentée également.
I - INTRODUCTION

Les stations sismiques du réseau permanent du Commissariat à l'Energie Atomique (C.E.A./ L.D.G.) sont situées entre 500km (pour celles du Sud-Est) à 1 100km (Nord-Ouest) de la région du Frioul. L'ouverture du réseau étant de 80° environ.

On a pu cependant enregistrer une partie importante de l'activité sismique, dans cette région, qui s'est déclenchée en Mai 1976.

II - DESCRIPTION SUCCINTE DU RESEAU

Il est composé de 20 stations télémétrées (sismographe C.P. Vertical) dont les données sismiques sont centralisées et enregistrées à Bruyères le Châtel (région parisienne), en permanence, sur enregistrement papier et bande magnétique. (Fig.1)

La bande passante des capteurs est de 0,5 à 20Hz environ, et les amplifications vont de 100 000 à 300 000 en déplacement à 1Hz suivant les stations.
III - LOCALISATION DES SEISMES

Pour calculer ces épicentres, le modèle moyen habituellement employé pour nos déterminations a été utilisé, à savoir un manteau à 25 km de profondeur avec des vitesses moyennes dans la croûte :

\[ V_p = 6.03 \text{km/sec} \quad V_S = 3.56 \text{km/sec} \]

et immédiatement sous la croûte :

\[ V_p = 8.16 \text{km/sec} \quad V_S = 4.65 \text{km/sec} \]

Nous avons présenté ces localisations (Table I) en les comparant à celles, prises comme référence, du Groupe de Travail du C.S.E.M. (Strasbourg, Novembre 1976), qui utilise un grand nombre de stations européennes entourant la région du Frioul, ainsi qu’un épicentre de référence (11 Mai 1976 - 22h 44 T.U.) enregistré localement par le réseau mobile de l’I.P.G. de Strasbourg. (cf. - Revised hypocenters and magnitudes determinations of major Friuli shocks 1976 -).

Nous avons constaté que si plusieurs phases sont lisibles sans ambiguïté, les localisations de notre réseau sont très voisines de celles obtenues par le C.S.E.M.

Les profondeurs sont par contre mal déterminées.

Les magnitudes \( M_L \) que nous avons calculées avec leurs dispersions sont indiquées dans la Table II et comparées à celles données par différents Observatoires comme Rome, Trieste, Strasbourg, Gräfenberg, ainsi que l'U.S.G.S.
La magnitude $M_L$ a été calculée pour chacun des séismes du Friouł que nous avons enregistré (354 séismes de Mai à Octobre) c'est-à-dire pour tous ceux dont la magnitude est supérieure à 2.5 environ, qui est le seuil de détection du réseau.

Les courbes fréquence - magnitude : $\log n = f (M_L)$ sont représentées successivement pour l'ensemble des séismes (Fig.2), pour le séisme du 6 Mai et ses répliques (jusqu'à la fin Juillet) (Fig.3), enfin pour le séisme principal du 15 Septembre (à 09h 20 T.U.) et ses répliques (jusqu'à la fin Octobre) (Fig.4).

Ces courbes ne sont linéaires qu'à partir d'une valeur de $M_L$ de l'ordre de 3.5. Pour les magnitudes inférieures à cette valeur, le coude observé reflète sans doute le défaut de déetectabilité de notre réseau. Par ailleurs, on peut constater une rupture de la courbe pour une magnitude voisine de 4.5 qui est suivie d'une discontinuité jusqu'à la magnitude 5.5 environ. Cette remarque ne se fait sur la courbe représentative de l'ensemble de l'activité sismique allant de Mai à Octobre, mais aussi séparément sur les courbes représentatives de celle correspondant au gros choc du 6 Mai et de ses répliques, ainsi que de celle du 15 Septembre et de ses répliques. Ajoutons que cette lacune n'est pas imputable à un manque de déetectabilité du réseau puisque son seuil de magnitude se situe vers $M_L \approx 2.5$

Les coefficients $b$ obtenus pour les séismes de magnitude supérieure à 5.5 ($b = 0.62$ pour les répliques du séisme du 6 Mai ; $b = 0.89$ pour l'ensemble des fortes secousses) sont faibles et indiquent un état de forte contrainte sur l'accident considéré.

Par contre, les coefficients $b$ obtenus pour les séismes de magnitude inférieure à 4.5, sont bien plus élevés ($b = 1.36$ pour les répliques du 6 Mai ; $b = 1.75$ pour les répliques du 15 Septembre ; $b = 1.38$ pour l'ensemble) et peuvent correspondre à des contraintes plus faibles sur l'accident principal ou sur des accidents mineurs.

Nous devons ajouter que les bornes de nos magnitudes 4.5 et 5.5 sont mesurées uniquement à partir des données de notre réseau et sont sans doute entachées d'erreur, mais les allures des courbes ne doivent pas être fondamentalement modifiées et les conclusions persistent.
V - EVOLUTION DE L'ACTIVITE SISMIQUE EN FONCTION DU TEMPS

Le choc principal du 6 Mai n'a pas été précédé de nombreux séismes, toujours au niveau de notre seuil de sensibilité, contrairement au choc du 15 Septembre 1976.

L'histogramme du nombre de séismes par jour après le choc principal du 6 Mai (jusqu'au 31 Octobre) (Fig.5) indique que l'on se trouve peut-être en face de deux phénomènes distincts : un séisme majeur sur un accident, suivi d'un autre séisme important sur un accident différent.

Ceci est partiellement confirmé par la migration des épicentres des répliques vers le Nord-Est de Mai à Septembre.

Sur la figure suivante (Fig.6) nous donnons le détail de l'évolution de l'activité sismique pour les deux séismes principaux 6 Mai et 15 Septembre, toujours à partir des données du réseau français du C.E.A./ L.D.G.

L'absence de précurseurs du séisme du 6 Mai (au moins au niveau de $M_L = 2.5$) traduit un état de contraintes assez uniformes dans un matériau homogène.

Au contraire, le séisme du 15 Septembre précédé de nombreux précurseurs est plutôt à associer à des contraintes non uniformes dans un matériau relativement hétérogène.

Nous avons également représenté l'évolution du nombre de séismes en fonction du temps :

$$n(t) = A t^{-p}$$

pour les deux essais de séismes (Fig.7)

Les coefficients $p$ obtenus :

$$p = 0.92 \quad (\text{séisme du 6 Mai})$$

$$p = 1.08 \quad (\text{séisme du 15 Septembre})$$

n'amènent guère de commentaires.
RESEAU SISMIQUE DU L.D.G.

Echelle: 1/5.000.000

- Station Centrale d'Enregistrement
- Stations Sismiques

Fig. 1
TABLE I: COMPARISON BETWEEN EMS C AND L D G LOCATIONS

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## TABLE II: Magnitudes of selected Friuli-earthquakes 1976

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**Explanations:**
- **RMP** = Roma, Monte Porzio
- **LDG** = Lab. de Géophysique, Paris
- **STR** = Strasbourg
- **GRF** = Gräfenberg
- **GS** = U.S. Geological Survey
- **TRI** = Trieste
SEISMES DU 6-5 AU 31-10
(354 evts M ≥ 2.5)

Fig. 2

I(1)  M: 3.5 → 4.4
log n(M) = 7.09 - 1.38 M  r² = 0.98

(2)  M: 5.5 → 6.5
log n(M) = 5.81 - 0.89 M  r² = 0.99

II(1)  M: 3.5 → 4.5
log n(M) = 7.36 - 1.46 M - 0.06 log(4.5 - M)
REPLIQUES DU SEISME DU 6 MAI JUSQU'A FIN JUILLET.
( 190 évts \( M > 2.5 \) )

I

I(1) \( M: 3.5 \quad 4.4 \)
\[ \log n(M) = 6.72 - 1.36 M \quad r^2 = 0.98 \]

(2)
\( M: 5.5 \quad 6.5 \)
\[ \log n(M) = 4.03 - 0.62 M \quad r^2 = 0.95 \]

II

\( M: 3.5 \quad 4.5 \)
\[ \log n(M) = 5.59 - 1.04 M + 0.31 \log (4.5 - M) \]

---

Fig. 3
REPLIQUES DU SEISME DU 15 SEPTEMBRE JUSQU'À FIN OCTOBRE.

I  M: 3.5  4.2
\[ \log n(M) = 7.90 - 1.75 M \quad r^2 = 0.97 \]

II  M: 3.5  4.3
\[ \log n(M) = 6.80 - 1.44 M - 0.34 \log (4.3 - M) \]

Fig. 4
NOMBRE DE SEISMES PAR 24h APRES L'HEURE ORIGINE DU CHOC PRINCIPAL.
(Magnitude superieure a 2.5)
NOMBRE DE SEISMES PAR HEURE APRES LE CHOC PRINCIPAL.

(Magnitude supérieure à 2.5)

SEISME DU 6 MAI.

SEISME DU 15 SEPTEMBRE.
REPLIQUES DU SEISME DU 6 MAI.

\[ \log n(t) = 1.42 - 0.92 \log t \quad r^2 = 0.49 \]

REPLIQUES DU SEISME DU 15 SEPTEMBRE.

\[ \log n(t) = 1.35 - 1.08 \log t \quad r^2 = 0.55 \]
NOTE ON FAULT PLANE SOLUTIONS RELATIVE TO THE MAJOR SHOCKS AND
SOME AFTERSHOCKS OF THE FRIULI AREA DURING
MAY TO SEPTEMBER 1976

by
A. Delhaye, B. Massinon, J.F. Rigaud
CEA, Laboratoire Detection et Geophysique
P. Mechler
Université Paris VI, Laboratoire de Geophysique Appliquée,
France

ABSTRACT
Using short period data recorded on the seismic network
of the Commissariat à l’Energie Atomique, similar data provided
by Italian stations, and that supplied by USGS (either Pg, or
Pn, or both phases), we have made an attempt to obtain fault
plane solutions for certain of the quakes which occurred last
year in the Friuli area.

In many cases, the lack of information on initial
movements combined with unsatisfactory distribution of reporting
seismic stations in azimuth do not permit us to arrive at clear
solutions.

Nevertheless, in certain cases, in particular those
involving the major shocks, we found that sufficient data was
available to arrive at probable solutions.

That could be the case of the main shock in May:
May 6: 20\textsuperscript{H}00' T.U.

and in September:
September 11: 16\textsuperscript{H}31' T.U.

for both of which, a strike slip solution along the alpine
direction is proposed (NNW-ENE). On the other hand, one could
find out some other solutions for aftershocks similar to this
one:

September 15: 9\textsuperscript{H}21' T.U.

which can be a thrust slip movement (SSW-ENE).

These results will be presented and their coherence
with known local tectonic situation discussed.
RESUME

Utilisant les données sismiques courtes périodes enregistrées par le réseau sismique du C.E.A., des données complémentaires de stations italiennes, et celles fournies par l'U.S.G.S. (phases Pg, ou Pn, ou les deux), nous avons essayé de construire quelques mécaniques au foyer correspondant aux séismes ayant eu lieu l'année dernière (1976) dans la région du FRIOUL.

Dans bien des cas, le manque de données sûres (premiers mouvements), et la répartition peu homogène de stations autour des épicentres ne nous permettent pas d'apporter de solutions claires.

Toutefois, pour les chocs principaux, nous atteignons des solutions fort probables.

C'est, comme nous le pensons, le cas du choc principal du 6 MAI à 20 h 00 T.U. et de celui du 11 SEPTEMBRE à 16 h 31 T.U. Sur chacun d'eux nous avons retenu une solution de coulissage le long de la direction alpine (NNO-ESE).

D'autre part, on trouve d'autres solutions pour les répliques de ces deux événements très voisins de celles du 15 SEPTEMBRE à 9 h 21 T.U. qui peuvent être envisagées comme une solution de compression (SSO-ENE).

Ces résultats sont présentés et leur cohérence avec la tectonique locale discutée.
Bien que nous ne disposions pas du sens de la première arrivée dans des stations proches de l'épicentre et que la couverture en azimut soit insuffisante, nous avons calculé le mécanisme au foyer des séismes les plus importants ayant eu lieu dans la région d'Udine.

Nous utilisons pour cela un programme qui teste le signe de la première arrivée dans des stations proches de l'épicentre.

Les précisions obtenues sur les paramètres des solutions proposées sont rarement inférieures à 15°.

Sur les 12 séismes étudiés, nous ne discuterons que sur ceux dont les solutions ne présentent pas une trop grande incertitude.

Notons que pour quelques séismes nous n'avons pu proposer de solution, que pour d'autres deux solutions sont possibles (faille de compression pure, mélange faille de compression-faille de décrochement) que pour d'autres enfin, une seule solution semble possible, notamment pour le séisme principal du 6 Mai 1976 à 20h 00.

Pour ce séisme les caractéristiques de la solution proposée sont les suivantes :

- **Plan A** : azimut : N 80°  
  pente : S 60°

- **Plan B** : azimut : N 140°  
  pente : NE 49°

- **Axe P** : azimut : N 198°  
  pente : 6°

- **Axe T** : azimut : N 297°  
  pente : 55°

Cette solution correspond à un décrochement sinistre sur le plan A ou à un décrochement dextre sur le plan B. Ces deux coulissages s'accompagnent par ailleurs de faibles rejets verticaux.
De même, le séisme du 11 Mai à 22h 44 nous incite à ne proposer qu'une seule solution (l'adjonction des données de deux stations proches, nous conduit à éliminer la solution faille de compression pure).

Nous obtenons les paramètres suivants :

Plan A : azimut : N 65°
         pente : 90° SSE

Plan B : azimut : N 155°
         pente : 30° ENE

Axe P : azimut : N 182°
         pente : 38° S

Axe T : azimut : N 308°
         pente : 38° NO

Le mouvement sur le plan A est un décrochement senestre pratiquement pur, sur le plan B le mouvement est moins bien déterminé.

En ce qui concerne les séismes de Septembre 1976, notons que la première réplique importante (11 Septembre 1976 à 16h 31) présente un mécanisme focal similaire à celui du choc principal. L'imprécision sur les paramètres de la solution est cependant plus grande.

Pour l'autre réplique importante (15 Septembre à 09h 22), nous retrouvons la possibilité de deux solutions. L'une correspond à une faille de compression pure, l'autre est un mélange des deux types, mais le type faille de compression est prépondérant.

Si l'on considère que les accidents ayant joué sont des accidents de direction semblable et que ces accidents ont joué sous l'influence des tensions de direction constante dans le temps, alors nous formulons l'hypothèse du rejeu d'accidents de direction alpine (NO - SE à ONO - ESE)

Dans cette hypothèse, si l'on admet un mécanisme du type faille de compression, les mouvements correspondent, soit à un plongement des Alpes sous l'Italie, soit à un plongement de l'Italie sous les Alpes, selon que l'on choisit l'un ou l'autre des plans possibles pour les solutions focales.

Au contraire, avec une solution du type faille de coulissage, les mouvements correspondent à un déplacement relatif le l'Italie vers l'Est, par rapport au reste du continent européen.
Pour certains séismes étudiés, le type faille de compression est impossible, mais en l'absence de données complémentaires, nous ne pouvons généraliser à l'ensemble des séismes étudiés.

D'autre part, la tectonique générale ne nous permet pas de lever l'indétermination. On sait que la plaque africaine remonte vers le Nord, en se déplaçant vers l'Est, ce qui peut provoquer l'ensemble des mouvements précédemment décrits. De plus, le bassin méditerranéen est formé par un ensemble de microplaques dont le mouvement relatif n'est pas connu avec précision.
6 MAI 1976   20 H 00 M 00.0 S

PLAN A : AZIMUT 80.0 DEGRES N
PENTE 60.0 DEGRES S

PLAN B : AZIMUT 140.0 DEGRES N
PENTE 49.1 DEGRES NE

AXE P : AZIMUT 198.2 DEGRES N
PENTE 6.1 DEGRES

AXE T : AZIMUT 296.9 DEGRES N
PENTE 54.6 DEGRES

PROJECTION DE L'HEMISPHERE INFERIEUR
SPACE-TIME DISTRIBUTION OF THE 1976 FRIULI EARTHQUAKE SHOCKS

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ABSTRACT

Results obtained by hypocentral determination of 700 shocks of the Friuli earthquake have been examined.

Special care has been devoted to the main shock. A comparison between focal parameters determined by analytical methods and macroseismic methods has been carried out.

The time and space evolution of the phenomenon has been followed by means of an array of local stations which allowed the determination of the hypocentres of about 700 aftershocks.

The analytical method based on S - P time interval has been employed, assuming a K-value of 7.5 km/sec.

An evaluation of experimental errors, performed by means of an original code, yielded an accuracy of ±2 km.

The study of hypocentres migration has shown seismic activity both to precede and to follow an event of greater magnitude.

Epicentre and hypocentre distributions plotted in order to depict the time-evolution of the phenomenon are shown in opportune intervals.

Results show interesting features of the seismic period which, in our opinion, warrant the pursuit of this kind of investigation.

RESUME

Au cours de cette étude, nous avons examiné les résultats de la localisation hypocentrale de 700 oscillations qui ont eu lieu au cours du tremblement de terre qui a secoué le Frioul à partir du 6 Mai 1976.

Une attention particulière a été portée au choc principal dont les paramètres focaux, évalués par méthode analytique, ont été comparés aux résultats obtenus par méthode macroisismique.

L'évolution temps-espace du phénomène sismique a été suivie au moyen d'un réseau de stations qui a permis de localiser l'hypocentre de 700 oscillations environ, utilisant comme méthode la différence Sg-Pg, le facteur K ayant pour valeur 7,5 km/sec.
Une estimation des erreurs expérimentales effectuée avec un nouveau programme de calcul a donné des résultats compris entre ±2 km.

L'étude des migrations d'hypocentres a mis en évidence une activité sismique comme symptôme prémonitoire ou conséquent à des secousses importantes ou catastrophiques.

L'évolution chronologique du phénomène a été tracée sur plans et sections pour des intervalles de temps déterminés.

La distribution des épicentres et des hypocentres tracée pour décrire l'évolution temporelle du phénomène est représentée pour des intervalles de temps fixés.

Les résultats obtenus ont mis en évidence des aspects très intéressants de la période sismique; ces résultats positifs encouragent la poursuite des études dans cette direction.
1. METHODS FOR HYPOCENTRAL DETERMINATION

The scientific interest and the remarkable social aspects of the event of May 6 suggested the immediate intervention of mobile stations of I.N.G. and of C.N.E.N. These stations operated in the area since May 7, in cooperation with the stations already existing at the dams of E.N.E.L. (2).

The development in time of the seismic phenomenon was followed continuously by the local seismic stations, which sometimes were displaced to improve their operation (5).

As known, the determination of the hypocentres can be made, starting from the data of local stations, through two calculation techniques substantially different. These can be reduced to the use of the only first arrival, or to the intervals between the arrivals of the longitudinal and trasversal waves. Without going into details concerning the two methods, it should be observed that the first method requires an accurate determination of the absolute first-arrival times or the availability of the telemetric seismic network. The second one, on the contrary, can leave out of consideration the absolute measurement of the time, but requires an accurate interpretation of the seismogram.

The difficulty involved in the synchronization of the clocks used in the network (increased in the first days by the frequent interruptions in the electric energy supply, by the bad reception of the time-signals, and by the displacements of the stations) suggested the use of the classic method based on the differences $T_{Sg} - T_{Pg}$. Such time is proportional to the hypocentral distance for the recording station, through the factor

$$K = \frac{V_{Pg}}{V_{Pg} - V_{Sg}}$$

An evaluation of the parameter $K$ can be made experimentally when a sufficient number of stations recording the same events (at least 4) is available. The tests carried out in this sense resulted in a mean value of $K = 7.5$ km/sec. This value was successively used for all the hypocentral determinations.

Taking into consideration the possibility that the parameter $K$ could vary as a function of the time and the space, in the area under examination, various tests were carried out to evaluate how these variations could affect the results obtained. It was thus confirmed that, for a variability range of the $K$ factor between the values of 7 and 8 km/sec, the scattering of the hypocentral coordinates was included in the variations related to the errors in the readings of time.

For the high intensity events, a comparison was possible
between the results obtained by using the calculation technique based on the first arrival method and that of the S - P method. The results are comparable for the events for which there were no doubts either about the phase interpretation or the time accuracy.

2. ERRORS INVOLVED IN THE HYPOCENTRAL DETERMINATIONS

A careful study referring to the accuracy of the results coming from the several techniques used was carried out.

2.1 The main shock

The hypocentral determination of the main shock, obviously carried out from the data coming from the pre-existing seismographic stations, was difficult because of the overlapping of the first pulse to the pulse of the foreshock.

In any case to carry out this determinationchema calculation programme based on the times of arrival of the first pulse from the different stations was used; the travel times experimentally derived by prof. Caloi (1) in the study of the earthquake of Cansiglio (1936) were used.

The results was the following (3):

\[
\begin{align*}
H &= 20.00 \pm 0.4 \\
\varphi &= 46.266 \text{ N} \pm 0.027 \\
\lambda &= 13.250 \text{ E} \pm 0.029 \\
h &= 20.1 \text{ km} \pm 3.8
\end{align*}
\]

It is necessary to make some considerations on the errors involved in such determination technique.

A first cause of error is related to the incertitude with which the arrival time of the P wave, dependent on the velocity of the recording system and on the frequency response of the instrument, is read. Moreover, it should be taken into consideration that the phase considered as the first one in the seismogram does not always correspond to the actual first pulse coming from the source. This may be more true for those stations receiving the wave coming from the nodal plane and for those which are situated at particular distances from the epicenter. Furthermore, the possibility that the nearer stations, that is to-say more sensitive, could record as a first pulse a phase which is otherwise mixed up with the noise in the recording of the farther, that is to-say less sensitive, stations, has to be carefully considered.

An evaluations of these errors, even if rather approximate, suggest to consider them within the confidence margins obtained with the least square method, previously discussed.
As far as the hypocentral depth is concerned, the greatest error which can be made in its determination is that of assuming a model of the propagation velocities rather different from the actual one. This systematic error is very difficult to quantify: several tests carried out using different models resulted in a wide variability field, while, on the contrary, the position of the epicentre remained constant (3).

The comparison of the result thus obtained with the results coming from a method of macroseismic investigation is very interesting.

The epicentral localization is generally made considering the cent of the most damages area as the epicentre. In this case this was found in area between Gemona, Trasaghis and Osoppo. The discrepancy between the analytical epicentre and the macroseismic epicentre is only apparent: in fact their definition is essentially different. The analytical epicentre is on the vertical line from the spot where the facture initially occurred. The macroseismic epicentre, located according to the damages caused to the structures, is normally on the vertical line from the spot of the focal volume nearest to the surface and can, furthermore, be affected by particular conditions of the surface geology.

The focal depth, as it is well known, can be calculated from the distance between isoseismic different degrees. Generally, the well-known formula is used (6):

\[ I_0 - I = h \log \left(1 + \frac{R^2}{h^2}\right)^{0.5} \]

In this case the formula gave the value of \( h = 11.8 \) km.

Another method to determine the focal depth is based on the Karnik's formula:

\[ M = 0.66 I_0 + 1.7 \log h - 1.6 \]

which correlates the magnitude, the epicentral intensity and the focal depth. Assuming \( I_0 = 9X-X \) MSK and \( M = 6.3 \), \( h \) resulted = 9.1 km.

The significance of these values of depth is to be found in that part of the focal volume where the energy release contributed for the greatest amount in causing the damages at the surface.

2.2 Aftershocks

Referring to the aftershocks, the error in the results giving the hypocentral coordinates derives from the uncertainty which the experimental data are read and depend on the number of stations and on their localization with regard to the hypo
centre.

The most important difficulty in the reading of the time difference S-P can be attributed to the detection by the operator of the exact arrival of the S phase in the seismogram.

Consequently to minimize this cause of error, all the seismograms for which interpretation doubts existed, were referred. Moreover, in the successive phases of the elaboration, all the data with anomalous residues were eliminated; also the analytically impossible solutions were not taken into consideration.

On reading without interpretation doubts, in the case of recording speeds of 60 mm/min, the possible error was evaluated at a value of about ± 0.2 sec. Such value, which we considered as the maximum value, is undoubtedly higher than that obtained with recording speeds of 120 mm/min or even with magnetic tape reproductions, as it is the case for same stations.

The consequences deriving in the detection of the hypocentre from such reading error, have been carefully analysed through a calculation programme on purpose prepared. The results rather interesting, evidenced the dependence of the error on the relative position of the stations with regard to the hypocentre of the shock.

When the stations are located all around the hypocentre, constituting a network the size of which is of the same order of magnitude of the hypocentral depth, the error of the hypocentral coordinates is included within ± 2 km, and the error on the depth is even lower. On the contrary, if the distance among the stations is remarkably lower than the hypocentral depth, the error on the depth is still of the same order of magnitude, while the error on the epicentral localization increases.

In the case of a network composed of stations remarkably more distant one from the order than in the previous cases, the epicentral position remains relatively sure in its assessment, while the depth results rather uncertain.

The most unfavourable case is shown by a network not surrounding the hypocentre; the stations supply data showing a remarkable scattering both the epicentral coordinates and of the depth.

A similar evaluation with reference to the analithical method based on the first arrivals was carried out too. Many observations are common to the two methods.

The first arrival method is more sensitive to the disposition of the seismic stations than the S-P method. The first arrival method in order to give good results need a quite uniform distribution of the seismic stations around the epicentres and the distances among the stations should be of the same order as the focal depth.

Among the examined nets, Figure 1 and 2 show the possible
epicentral positions and depth, as shown by arabic numerals (cfr. perag. 3) for fifty solutions for the first arrival and S - P method respectively, considering a random error up to ±.2 seconds for each seismic station.

3. SPACE-TIME DISTRIBUTION

Interpreting the seismograms recorded by the local stations, it was observed that the values of the hypocentral distances were constant for short periods of time. This observation suggested us to deepen the study to evidence the possible duration of the seismic activity in given zones of the interested area. For this purpose a calculation programme was adopted which supplied the graphs showing the location of the hypocentres of the shocks for particular periods of time. The groups of hypocentres often contained a shock of relevant magnitude; its seismogram showed important analogies with the seismograms of the minor shocks, recorded in the same station.

First of all the epicentral positions of the shocks included between two events with high magnitude were plotted on maps. However, these graphs, though giving a clear representation of the migratory phenomenon, did not completely describe its complex trend.

Successively, the area interested by the seismic phenomenon was subdivided into circular zones having an adequate radius. The circular zones were centred for the most part on the epicentral positions of the shocks having higher magnitude. Thus the events occurred within the examined zones were evidenced in chronological order. The results obtained showed the appearance of the seismic activity in zones surely inactive, either as rewarding signs of more important events, or as phenomena following such events (see Table I and II).

The periods of time characterizing such phenomena supplied us with a subdivision to be used for further maps of the epicentres. With reference to the same periods of time, N - S sections were also prepared, where the positions of the epicentres are represented.

Of the whole series of 26 maps referring to the hypocentral and epicentral distribution vs. time, 11 are reported in Figures 3 a, b - 13 a, b.

Epicentres distributions (letter a) has been obtained by a computer output in a 1:100.000 scale.

In these maps each event is represented by number indicating the depth in discrete classes of two kilometers. For instance, the number 0 indicated a depth between 0 and 2 km, and so on: number 9 indicated a depth higher than 18 km. When the number is accompanied by an asterisk, this indicates an event with a
magnitude equal or higher than 4.

The sections, also derived from an original scale of 100,000 are shown in figures 3b - 13b. In these figures the epicentres are indicated with little crosses when the magnitude is lower than 4, with asterisks when the magnitude are higher.
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Fig. 1
Map showing the possible epicentral solutions for the shock of 9.11 at 16.31 obtained by means of the $S - P$ method with a maximum random variation of $\pm 0.2$ sec. off the time readings.

Fig. 2
Map showing the possible epicentral solutions for the shock of 9.11 at 16.31 obtained by means of the first arrival method with a maximum random variation of $\pm 0.2$ sec. on the time readings.

Fig. 3a-b from 5.11 to 5.12
The focal depth reaches values of 20 km. No very clear preferential alignments are shown; a quite vertical alignment is outlined; epicentres show an alignment in a E-W direction.

Fig. 4a-b from 12.5 to 15.5
The seismic activity is concentrated in the North-eastern part of the investigated area; the epicentres show a horizontal alignment with a concentration at the depth interval comprised between 7.5 and 10 km. Some hypocentres show focal depths up to 15 km.

Fig. 5a-b from 5.23 to 5.25
The seismic activity is located in a wide area in the central southern zone; hypocentres show an alignment dipping with small angle towards North; focal depths are comprised between 5 and 13 km.

Fig. 6a-b from 5.25 to 5.29
The seismic activity interesting the central part of the investigated area shows a weak shifting towards North. The hypocentres in the northern part show depths up to 18 km. An alignment dipping towards North is shown too.

Fig. 7a-b from 6.3 to 6.8
The epicentres seem to be aligned in a WSW-ENE direction with a higher concentration in the West side; the hypocentres are located at a depth from 7 to 15 km.

Fig. 8a-b from 6/8 to 6/30
The distribution of the epicentres show an alignment in an ENE-WSW direction with a clustering at the eastern an western part of the investigated area. This could be a sign of the butterflied fault where the seismic activity is concentrated
in the sides of the fault. The focal depths reach values up to 15 km.

Fig. 9a-b from 9.11 to 9.13
The increased seismic activity following the 9.11 at 16.31 event shows a concentration in the North-eastern part of the investigated area. The hypocentres are clustered at depth of 7 km and show an alignment dipping towards North with a small angle. On the contrary, in the Northern part of the area the alignment of the hypocentres is towards South.

Fig. 10 a-b 9.15 from 03.55 to 17.26
The events reported in Figure follow that of the 03.15 with magnitude 6.1. They seem to be more clustered in a North sector than the other previous events. The epicentres show an alignment in a E-W direction. The hypocentres alignment is vertical and reach the depth of 13 km.

Fig. 11a-b from 9.15 to 9.17
The epicentres are widely diffused with a clustering in the northern part of the investigated area. The alignment of the hypocentres is towards South and they reach the depth of 22 km.

Fig. 12a-b from 9.25 to 10.1
In the Northern sector the activity is continuing. Also the alignment of the hypocentres has still a dipping towards South.

Fig. 13a-b From 10.1 to 10.4
The seismic activity has a low intensity, prevailingly concentrated in the northern sector. The hypocentres alignment is towards South and reaches a maximum value of 12 km.