Instituto Panamericano de Geografia y Historia

Final Report

Seismic Hazard in Latin America and the Caribbean

Volume 1

Project Catalogue and Seismic Hazard Maps

By

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Foreword

The original proposal for this project was put together at a workshop held in México at the secretariat of IPGH during the summer of 1989. Present at the meeting were Sylvain Dufour of IDRC, Dr. Gerardo Suárez from México (UNAM), Dr. Aristóteles Vergara from Central America (CEPREDENAC), Ing. Alberto Giesecke from South America (CERESIS), Dr. John B. Shepherd from the Caribbean (SRU/UWI) and J.G. Tanner and Ing. Leopoldo Rodriguez (Secretary General) of IPGH[1]. Those of us from out of town were staying at the Hotel Emporio in the centre of México City.

The first morning we met after breakfast in the coffee shop of the hotel just prior to leaving for the offices of IPGH. While we were enjoying a coffee, the city was struck by a large earthquake (about magnitude 7) which occurred a couple of hundred kilometres to the southwest of the city. The group moved quickly to an archway to wait out the earthquake. The motion lasted for nearly thirty seconds, near the end of which loud cracking noises could be heard from the upper part of the building, giving the impression that if the shaking continued there would likely be damage to the building. Fortunately, the movements ceased at that point as did the pandemonium in the coffee shop.

After the earthquake the streets were full of people, many of whom had scurried there during and after the earthquake. There was no significant damage to any of the buildings in the vicinity of the hotel and we felt fortunate to get off with only a severe shaking. While perhaps a more normal experience for the residents of the city, the event was unsettling to those of us not accustomed to the effects of large earthquakes on México city. Two of us took note of the magnitude of the motion of the building and agreed afterward that it was about two feet peak to peak.

This rather auspicious start to what eventually became an approved project of IDRC set the tone for this study of seismic hazard in Latin America and the Caribbean. The frightening nature of the experience was a sharp reminder of the possible ravages of earthquakes and emphasized to us one aspect of a damaging earthquake that seems so often forgotten - that of the emotional trauma particularly in the case where there are personal losses or injury to family members and/or close friends. In its own way, this experience possibly contributed to the decision by some of the participants to undertake this study (a study that will continue beyond the life of this project) of the effects of earthquakes through recorded time on the social and economic life of the citizens of their respective regions.

Those of us from countries where the tectonics are much quieter have little comprehension of the devastation suffered by the citizens of any area due to a damaging earthquake, to say nothing of the trauma associated with other geological hazards such as volcanoes. We are, however, frequently asked to help out in the event of disasters caused by earthquakes by providing emergency relief and perhaps equally importantly, funds and expertise to assist in the development of technical activities designed to provide improved monitoring of earthquakes or volcanoes. This latter is an important contribution, but much more lasting if accompanied by longer term efforts to

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[1] See the first page of the Introduction which follows immediately for an explanation of these acronyms.

quantify the hazard using the talents of the local specialists throughout the region. This project is one such effort in this direction, but as successful as it has been we should remember that it is a start only. Further studies should follow to extend our understanding to the effect of soils on seismic waves for example and to develop wherever possible a similar capability in the case of other geological hazards.

Finally, this project proved far more complex and time-consuming than originally estimated. Many long hours were spent at the computer by all involved in a concentrated effort to produce a product, consistent with conventional international standards, that meets the needs of the local constituencies. No doubt at least some of us were spurred on by the experience in México.

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Introduction

The vastness of the project area and the attendant number of individuals and institutions concerned with seismicity and seismic hazard dictated a style of operation that was regional in character. Four organizations (see below), in addition to the Instituto Panamericano de Geografia y Historia (IPGH or PAIGH), formed the core of the project and in turn each was responsible for contacts with agencies and individuals from within their respective regions. Contacts involving local agencies and individuals is a *sine qua non* for any successful project in Latin America and the Caribbean - local authorities will always look to the local experts for advice and they in turn will seek information at the regional or continental level to place their advice in context.

The organizations involved in the project are:

- Universidad Nacional Autónoma de México - UNAM - located in México City,
- Centro de Coodinación para la Prevención de Desastres Naturales en América Central - CEPREDENAC - headquarters in Guatemala,
- Centro Regional de Sismologia para América del Sur - CERESIS - headquarters in Lima, Perú,
- The Seismic Research Unit of the University of the West Indies - SRU/UWI - located in St. Augustine, Trinidad.

Originally the contact from CEPREDENAC was its Secretary General, but subsequently this responsibility was transferred to the Director of the Escuela Centroamericana de Geologia of the Universidad de Costa Rica - ECG/UCR - located in San José, Costa Rica - where it has remained for the last four years of the project.

The project was overseen by a Steering Committee composed the Project Leader of IPGH and individuals nominated by the adhering agency. The meetings were entirely open and representatives of related projects and organizations from outside the area were invited to attend its meetings without vote. This Steering Committee met about once per year contemporaneously with a technical workshop which consisted of presentations on topics of current interest to the project. This connection with the technical activities helped the Steering Committee simplify its discussions and avoid the possibility of taking the wrong route for any activity.

Given this simplified management structure with its strong connections to the technical activities, the project proceeded iin a straightforward manner despite problems with maintaining its original schedule. Indeed, one such delay forced the Project Leader to take a much more active role than originally foreseen to overcome the loss of almost a year of technical activity at the project level.

The project also proved to be much more complex than originally forecast. We had to allow additional time at the local level to complete and approve both the local and regional catalogues and seismic hazard (ground motion) estimates. Any effort to jump these hurdles would have led inevitably to reduced quality of the outputs, undoubtedly to major dissatisfaction at the local level and possibly to compromise of the outputs of the project.

Within the limitations imposed by the above a two phase project, first the catalogue and then the hazard estimates, unfolded which unfailingly started with the fundamental work at the local level followed by the regional and project level actions. Under this regime any early delays at the project level were quickly overcome. Research time was also spent on such things as software and the method of conversion to moment magnitudes, the magnitudes computed by local seismologists and compiling information available from global centres such as the ISC and NEIS, all of which proved to be of enormous benefit. Although the catalogue took by far the longest time at both the project and regional level, the results appear to justify the extra effort.

By the time the hazard calculations were completed, the official end of the project had been reached and the final phase, writing up and presenting the results to the community, was underway. At this point, however, renewed activity, after a century of quiet, at the Soufrière Hills volcano in Montserrat led to delays as one of the authors of this report (JBS) spent about two years travelling back and forth from the UK to Montserrat. This situation was not entirely bad as favourable publicity accrued to the project through the excellent work of Dr. Shepherd.

The only major deviation from the plan originally set up by the Steering Committee concerned secondary catalogues, such as an index of publications, a compilation of first motion results, an index of strong motion recordings and other such quantities that relate to a compendium of epicentres and magnitudes for earthquakes. Of these only the bibliographies were carried out at the project level. This departure was not due to time limitations, but rather the view of the Steering Committee that activities at the project level should compliment and not replace those at the local and regional levels. Put simply, the compilation of these additional catalogues was seen as too much a duplicative effort and therefore abandoned. The bibliographies on the other hand were regarded as the key to directing individuals to the proper local experts and therefore were pursued at the project level.

The bibliography was approached from six perspectives. These were respectively a bibliography of publications produced by the participants in the project (Appendix I), bibliographies relating to the earthquake catalogues of each of the four regions (Appendices II through V) and a generalized bibliography of seismic hazard on a global scale (Appendix VI). In the case of Appendices II to V, the bibliographies were limited to providing a key for interested students to pursue seismicity studies in the particular region in greater detail. The same may be said of Appendix VI which is intended only as an overview of global efforts.

The Steering Committee actively encouraged all participants to publish their results as soon as possible with the result that there is an extensive list of contributions from the project. To aid the process of dissemination of information, the project published several technical reports which consisted of mainly presentations made at the annual workshops. These compilations also served to fulfil the requirement of IDRC for annual reports. The bibliography of contributions from the project is given in Appendix I.

In this report the project catalogue and associated software are presented first followed by a discussion of the hazard calculations complete with a presentation of the methodology and software. Finally the maps computed at the project level are presented and discussed in the context of the results obtained by each of the regions and the procedures laid down by the Steering Committee. Basically, each region was responsible for the computation and the approval of its hazard maps and the writing of the report to accompany the map. At the project level, the Steering Committee directed that we compute a reference map using a method specially developed for this purpose. This map would serve as a means of comparing seismic hazard in one area to that in another.

In the remainder of this introduction, the main results of the meetings of the Steering Committee are presented briefly to relate the activities of this body to the progress with the project and to provide some background understanding of why activities were undertaken in the manner described.

Meetings of the Steering Committee

Seven meetings of the Steering Committee took place over the life of the project which, except for the first, were accompanied by a technical workshop to provide a forum for discussion of current problems. These meetings took place at the following times and locations:

- London, Ont., Canada - June, 1990
- Panamá, Republica de Panamá, February, 1991
- Melbourne, Florida, March-April, 1992
- Melbourne, Florida, March, 1993
- Brasilia, Brasil, August, 1994
- Melbourne, Florida, December, 1994
- Melbourne, Florida, May, 1995

Each of these meetings typically lasted a week with a technical workshop on the topics of the day preceding the meeting of the Steering Committee, which usually took place an the last day. The Steering Committee made a number of important decisions which are summarized briefly here without comment.

> (i) The meetings of the Steering Committee would be working meetings in the sense that the project office was required to provide computing power adequate to test ideas and hypotheses under consideration.

(ii) All outputs at the project level would complement and not replace local and regional results because the project wished to emphasize the importance of local activities.

(iii) The project catalogue would also give preference to local and regional solutions to earthquake occurrences over those obtained from central sources such as the International Seismological Centre and the US Geological Survey

(iv) Originally the Steering Committee recommended the use of M_s as the magnitude to be used for the hazard calculations at the project level, but this was subsequently modified to the use of M_w to be consistent with the Global Seismic Hazard Project (GSHAP).

(v) The project could not meet all of the specifications of the GSHAP project, but cooperated in every way possible within the time available.

(vi) Each region would be responsible for producing a seismic hazard map using a method of its choice and the project (IPGH) would be compile a five level seismic hazard map to serve as a link among the regional maps - the five levels were defined as follows:

- 0 to 62.5 gal (cm/s^2) - minor hazard level
- 62.5 to 125 gal - low hazard level
- 125 to 250 gal - moderate hazard level
- 250 to 500 gal - significant hazard level
- Greater than 500 gal - high hazard level.

(vii) México, Central America and South America decided to compute their maps by the source zone method and the Caribbean by both the source zone and historic parametric methods - IPGH would use a version of the historical parametric method developed specially for the project.

(viii) Each region and IPGH would produce a final report of no more than 100 pages which IPGH would reproduce for distribution.

(ix) Supported the effort of the Caribbean to establish a region-wide seismology group for the purpose of exchanging information, compiling a regional catalogue, etc..

(x) At the request of the International Development Research Centre in Ottawa, Canada, approved a new project proposal that contained several elements related to seismic hazard and submitted it to the project officer of IDRC who originally indicated that he would attempt to broker it among other agencies in the business of providing aid to developing regions. Unfortunately we lost our friend in court through promotion and this effort has fallen by the wayside.

(xi) Adopted a policy throughout the life of the project of encouraging timely publication of results and cooperation with other projects where feasible.

Membership of the Steering Committee.

At the beginning of the project the membership was:

J.G. Tanner - IPGH,

J.B. Shepherd - Caribbean - SRU/UWI,

G.Suárez - México - UNAM,

A. Vergara - Central America - CEPREDENAC,

A. Giesecke - South America - CERESIS.

As might be expected changes took place over the five year interval of the project and at its conclusion the Steering Committee membership was:

J.G. Tanner - IPGH - Project Leader

J.B. Shepherd - special adviser for the Caribbean and to IPGH

R. Zúñiga - UNAM

W. Montero - ECG/UCR (Central America - CEPREDENAC)

A. Giesecke - CERESIS

L. Lynch - SRU/UWI

Acknowledgements

First and foremost we must acknowledge the efforts of all the seismologists and technicians involved with ongoing recording and evaluation of seismic records to produce the basic data for the project and regional catalogues for those events that have occurred since about 1900. As subsequent text will establish, their work has been of uniformly high quality throughout the project area and enabled us to produce a reliable catalogue using moment magnitudes to describe the size of the particular event. While we could not possibly cite them individually or their institutional affiliations, their work is the one of the most important contributions to the project

catalogue. The Steering Committee is profoundly grateful to these individuals and to their institutions for sharing with us the results of decades of labour.

In a similar vein we must acknowledge the efforts of all those involved in compiling historical information on earthquakes and in interpreting these archival records to produce the entries in our catalogues. The interpretation of this information is always equivocal, but this in no way should detract from the splendid effort of the individuals and institutions concerned. Again, nearly all institutions in the project area have contributed and again we are grateful for their willingness tor share their results with the project and the international community.

The Secretary General of IPGH has been a constant supporter of the project and has lent the support of his office to the achievement of the goals of the project. His enthusiasm and positive outlook have been an asset to the project from its inception. No acknowledgement could be complete without complementing the work of the staff of the Secretary General's office of IPGH. The project leader, who spent nearly six months in México on the project, is particularly grateful for the help of the staff of the Institute in the many phases of the project, despite its being an addition to their regular responsibilities. Their cheerful and positive attitude contributed enormously to what turned out to be a very pleasant, enjoyable and productive assignment.

The project leader must also acknowledge the enormous contribution of UNAM to his stay in México. The Instituto de Geofisica generously recommended to the university that he be granted a visiting fellowship and provided access to all the facilities of the university, including a "cubiculo" vacated by their representative on the Steering Committee while on sabbatical. The professional and technical staff of this large and well regarded institute were to a person supportive of this work and helpful whenever required. Without doubt the stay in México was made much more pleasant and productive by the contribution of this institution and its staff.

The project officers of IDRC are all thanked for their flexibility in dealing with unusual situations which always seemed to arise in this project which, as previously mentioned, proved far more complex and difficult than forecast at its outset. Had we been forced to proceed along the lines originally laid out in the original budget, the outcome could not have been achieved to say nothing of the effect on the quality of the outputs. The cooperation of the officers concerned was a major factor in minimizing the normal tensions associated with a project which set out a comprehensive and ambitious set of goals with relatively modest funding.

The project leader would also like to thank both the patience and contributions of his wife, Patricia, to the project. She tolerated the use of what seemed to be an ever increasing percentage of the house for the project and, of course, contributed her many skills in office management, writing and editing of documents, organizing workshops and meetings of the Steering Committee and generally assisting the project in any way she could. She did so from the outset to the final stages of the project when she was forced to limit her involvement because she took on another job.

The project leader would like to acknowledge the enormous contributions of the members of the Steering Committee to the project. Their friendship, unfailing good spirits and positive attitude despite constant "hounding" by the project leader were prime factors in the success of the project. The efforts of Dr. John Shepherd, the representative of the Caribbean initially, but later a special advisor to the project, deserve special mention because they were an enormous influence in achieving the goals of the project. His knowledge of seismicity in the project area is unique and provided the technical basis for many of the judgements necessary in the compilation of the project catalogue, without which, it may be added, the quality of the catalogue would have suffered enormously. The project leader, while not a seismologist, learned an enormous amount about this fascinating science directly through the contributions of Dr. John Shepherd.

Finally, we would like to acknowledge the contributions of Prof. Lalu Mansinha of the Earth Sciences Department of the University of Western Ontario, Mr. Peter Basham of the Geological Survey of Canada and Dr. Kaye Shedlock of the United States Geological Survey. Prof. Mansinha attended several of the workshops and Steering Committee meetings and contributed many valuable comments to these meetings. He also served as an outside reviewer of the project along with Peter Basham and kindly reviewed the final report.. Peter Basham was also the contact with the Global Seismic Hazard Project (GSHAP) and provided much valuable advice during the course of our many contacts throughout the life of the project, including a review of the final report. Dr. Shedlock is particularly thanked for a very thorough editorial and techncal review of the penultimate version of this report.

Organization of final reports

As indicated on the title page this is Volume I of what is intended as a series of reports comprising five volumes, each of which will be bound separately and available through the Secretary General of IPGH. The other volumes are respectively:

Volume (Capitulo) II - México
Volume (Capitulo) III - América Central
Volume (Capitulo) IV - América del Sur
Volume (Capitulo) V - Caribbean (El Caribe)

At the time of writing of this volume (Volume I), the reports for México, América Central and América del Sur are in hand and will be printed at the same time as Volume I. We have no estimate of the time of availability of the report from the Caribbean.

The Project Catalogue

Summary

The agencies (UNAM for Mexico, CERESIS for South America, CEPREDENAC for Central America and UWI for the Caribbean) from each of the four regions comprising the project (in addition to IPGH) have assembled revised catalogues of historical and instrumentally recorded seismicity. Each has been incorporated into a project catalogue, following guidelines set down by the Steering Committee, with the aid of software specially written for the purpose by the Geophysics Commission of IPGH.

As this catalogue is intended primarily for use in the computation of estimates of ground motion (velocity and/or acceleration), considerable time and effort was spent on the problem of multiple solutions to the same event. Time- and space-based windows of varying sizes were placed on the events in the catalogue and each pair of events identified by the software was examined to determine whether or not both represented solutions to the same event. In cases of duplicated solutions one was identified as the primary solution (an asterisk in column 1) and the other(s) as secondary (a blank in column 1). According to the policy of the Steering Committee, regional solutions to events were given preference unless there was good reason to proceed otherwise.

The original catalogue compiled by this extensive and time-consuming procedure contained over 100,000 unique events distributed over the geographic area bounded by 60°S, 33°N, 30°W and 120°W covering a period ranging from 1471 to the middle of 1994. Approximately one-half of the events contained at least one magnitude estimate of some type, the remainder serving as information useful in defining patterns of seismicity. About 2600 of these events are regarded as historical, having occurred prior to 1900. Finally, the formats adopted for the catalogue is that used by the International Seismological Centre (ISC) in the United Kingdom and the SISRA format (created by CERESIS for the original compilation of the earthquake catalogue for South America) used most commonly for data exchange among the groups involved in the project.

Considerable thought has gone into which magnitude type might best serve the seismic hazard calculations. At a meeting in 1993 the Steering Committee recommended the use of M_s for this purpose, but subsequently a decision was taken to use of moment magnitude (M_w) to be consistent with the Global Seismic Hazard Project (GSHAP) being undertaken under the aegis of International Lithosphere Program as part of the UN's International Decade for Natural Disaster Reduction. Accordingly, some 1200 moment magnitudes for events in the project area have been taken from various sources to establish a scale for estimating moment magnitudes of other types (M_s and m_b). A second catalogue has been derived which contains moment magnitudes (original and estimated) as the primary magnitude estimate.

Both the original and derived catalogue have been extensively tested resulting in a number of improvements in them. One of these tests has been the computation of seismic hazard estimates using a method, which is extremely fast on a computer, specially developed for the purpose. This method has proved so successful that the Steering Committee recommended it use for the computation of a "reference level" map for the project area.

Resumen

Las agencias (UNAM por México, CERESIS por América del Sur, CEPREDENAC por América Central y UWI por el Caribe) de cada una de las cuatro regiones que comprende el proyecto (además del IPGH) integraron catálogos revisados de sismicidad histórica y registrada instrumentalmente. Cada uno de ellos fue incorporado en un catálogo de proyecto, siguiendo los lineamientos establecidos por el Comité Directivo, con la ayuda de programas escritos especialmente para este propósito por la Comisión de Geofisica del IPGH.

Como la primera intención de este catálogo es para usarse en el cálculo de estimaciones de movimientos del terreno (velocidad y/o aceleración), se invirtieron tiempo y esfuerzos considerables al problema de soluciones múltiples de un mismo evento. Se aplicaron ventanas espaciales y temporales de diveros tamaños a los eventos del catálogo, y se examinó cada par de eventos identificados por el programa para determinar si éstos representaban o no soluciones a un mismo evento. En los casos de soluciones duplicadas se indentificó una de ellas como la solución primaria (un asterisco en la columna 1) y la(s) otra(s) como secundarias (un blanco en la columna 1). De acuerdo a la política del Comité Directivo, se le dio preferencia a las soluciones regionales para los eventos a menos que hubiera una buena razón para proceder de otra manera.

El catálogo original compilado con este procedimiento extenso y laborioso contenía más de 100,000 eventos únicos distribuidos en toda el área geográfica delimitada por 60°S, 33°N, 30°W y 120°W cubriendo el periodo de 1471 a mediados de 1994. Aproximadamente la mitad de los eventos contenían al menos una estimación de magnitud de algún tipo, el resto sirvió como información útil para definir los patrones de sismicidad. Cerca de 2,600 de estos eventos son considerados como históricos, habiendo ocurrido antes de 1900. Finalmente, para el catálogo se adoptaron los formatos utilizados por el Centro Internacional de Sismología (ISC) del Reino Unido, y para el intercambio de datos entre los grupos involucrados en el proyecto se utilizó más comúnmente el formato SISRA (creado por CERESIS para la compilación original del catálogo de terremotos para América del Sur).

Se le dedicó mucha atención a qué tipo de magnitud serviría mejor para los cálculos de peligro sísmico. En una reunión en 1993 el Comité Directivo recomendó el uso de M_S para este propósito, pero posteriormente se tomó la decisión de usar la magnitud de momento (M_W) para ser consistentes con el Proyecto de Peligro Sísmico Global (GSHAP), auspiciado por el Programa Internacional para la Reducción de los Desastres Naturales, de las Naciones Unidas. De acuerdo con esto, se tomaron de diversas fuentes alrededor de 1,200 magnitudes de momento eventos en el área del proyecto para establecer una escala de estimación de magnitudes de momento de otros tipos (M_S y m_b). De aquí se elaboró un segundo catálogo que considera las magnitudes de momento (originales y estimadas), como la estimación primaria de magnitud.

Tanto el catálogo original como el que se derivó de éste, han sido probados extensivamente dando como resultado varias mejoras en ellos. Una de estas pruebas fue el cálculo de

estimaciones de peligro sísmico utilizando un método especialmente desarrollado para este propósito, el cual es extremadamente rápido en computadora.

Este método probó ser tan exitoso que el Comité Directivo recomendó su uso para el cálculo de un "nivel de referencia" para el área de proyecto.

Introduction

An earthquake catalogue with uniform magnitude determinations and estimates of the time periods and magnitude ranges for which it is complete is an essential requirement of probabilistic estimates of seismic hazard. Until now no such catalogue has existed for the project area with the result that previous estimates of seismic hazard with a given probability of exceedance have been subject to large uncertainties, particularly with respect to the comparison of computed values from various regions within the project area. In this section we describe briefly the procedures used to compile a project catalogue for the entire area of Latin America and the Caribbean (bounded by 60°S, 33°N, 30°W and 120°W) covering the period 1471 to the middle of 1994.

The intent of the catalogue is not to replace the existing regional and local catalogues, but rather to supplement them and to provide a tool for the calculation of uniform seismic hazard estimates across the project area. These latter serve as a basis for comparison of hazard estimates from various regional and local sources within the project area which is increasingly desirable considering the international nature of commerce.

The catalogue is in machine readable form in the Kintbury format of the ISC which is described in Appendix VIII. Each earthquake is identified by a unique 15 digit code consisting of the date and time of the event to the nearest one-tenth of a second. This identifier has been used extensively by the software system know as "MANAGE" (Tanner et al, 1992) written specially for the compilation, evaluation and retrieval of events contained in the catalogue. A brief description of the functions carried out by this software is given later in this chapter.

Originally, the plans of the Steering Committee called for the compilation of catalogues containing supplementary information such as focal mechanisms, intensity maps, tectonic maps, a bibliography and other information relevant to particular earthquakes. As these were also a priority with the regional and local agencies involved in the project and as the Steering Committee adopted the policy of not duplicating information readily available from regional sources, only the bibliography has been attempted at the project level. The results of this undertaking are given in the Appendices I to VI. As with the project catalogue these have been compiled as a supplement to regional and local bibliographies and are not intended to replace them. Appendix VI contains a representative bibliography of seismic hazard research, which the Steering Committee believed to be an important undertaking at the project level and one not likely to be duplicated at the regional and local level.

Sources of Information for the Catalogue

The principal sources of our compilation are:

(i) The epicentre catalogue of the ISC for the period 1898 to mid-1994. This catalogue served as the baseline and initially all events contained in it were included. The ISC catalogue includes data from the U.S. National Earthquake Information Center (NEIC), the International Seismological Summary (ISS), the Bureau Central International de Sismologie (BCIS) and several standard, classical catalogues covering all or part of the project area such as those of Gutenberg and Richter (1954) and Sykes and Ewing (1965). The prime sources for the ISC catalogue are listed in Appendix IX.

(ii) The South American catalogue of the SISRA project and its subsequent extension to the end of 1991 which includes data from all national catalogues of the countries of South America. This catalogue includes solutions to events from both macroseismic (generally prior to 1900) and instrumental sources.

(iii) The Mexican catalogue of instrumental epicentres compiled by R. Zúñiga (1992) for the period 1899-1992.

(iv) The historical catalogue for México compiled by Gerardo Suárez of UNAM. Time limitations allowed 20 seismic interpretations of records to be made for only the most significant historical events (about 20 in this case). This important work is continuing.

(v) The Central American catalogue of Rojas et al (1993) which includes national catalogues from all the countries of Central America for the period 1900-1991. The original version of this catalogue was compiled in Norway, but many subsequent improvements and additions were made by Rojas for our project catalogue.

(vi) The macroseismic catalogue for Central America compiled by Walter Montero of the Universidad de Costa Rica (Instituto Centroamericano de Geologia (ICG)). This catalogue contains solutions to events occurring in the historical era (from the early 1500s) and the instrumental era (up to about 1930).

(vii) Catalogues of the Seismic Research Unit of the University of the West Indies (SRU/UWI) for the period 1953-1991. For the period July, 1976 to December, 1991 all events have been relocated using the Joint Hypocentral Determination and regional travel-time tables (Shepherd et al, 1987). Included in this catalogue are solutions provided by the Institut de Physique du Globe (IPG) of the University of Paris and national catalogues from Puerto Rico, the Dominican Republic and Cuba.

Space prevents listing the numerous contributions from other individuals and agencies active in seismic research throughout the project area. Many recomputed epicentres, depths and magnitudes have resulted from their efforts. These sources are identified in the catalogue (see Appendix VIII for a listing of sources used in the catalogue).

Funding and time limitations did not permit the establishment of more extensive contacts with agencies in the highly diverse Caribbean area. We did manage to extend the contacts significantly at the end of the project and were able to incorporate at least some of their suggestions and data into the project. Addresses of the individuals in the Caribbean with whom we managed contact are listed in Appendix VII. We strongly recommend they be contacted in the event any individual wishes to pursue further research on events in the Caribbean.

Types of Record

The project spent considerable time in workshops discussing the complex and difficult question of macroseismic determinations of seismicity. Individuals such as J. Grases of Venezuela have spent a significant part of their career on this subject and have made valuable contributions to at least two of the workshops. Indeed some measure of agreement was reached among the participants in one of these workshops regarding the form and procedures for macroseismic determinations. We hope that J. Grases will continue this effort, eventually leading to a publication of this discussion. The project also sponsored a technical meeting in Central America organized by Ing. Walter Montero (ICG/UCR) to discuss macroseismic determinations of seismicity for Central America. The results are manifested in the improved quality of the macroseismic catalogue for this region.

A short discussion of the macroseismic and instrumental entries in the catalogue follows. This brief summary should be read in the context of the effort made by the project to improve the quality of both types of record. However, there should be no suggestion that ours is the final word. The work on a catalogue is both mammoth and never-ending and we have no doubt that creative individuals will in future come up with substantial improvements to the quality of the solutions for seismicity in the project area.

(a) Macroseismic data

Locations and magnitude estimates made from macroseismic data for all events prior to 1898 within the four regions have been included in the project catalogue. The Mexican macroseismic catalogue is incomplete, containing solutions only to the most significant events. For South America and Central America all felt events are included and the methods of estimation of epicentre coordinates, magnitudes, etc. are explained in SISRA (1985) and Rojas et al (1993). The catalogue therefore contains a large number of events for which only one intensity report is available and likely includes many aftershocks of major events.

For the Caribbean (Shepherd and Lynch, 1992) only those events felt at intensity VI or greater, or felt over a wide area, are included. This approach was necessary because of the geography of the region which is a series of islands (relatively small for the most part) in a much larger area of water cover. As most of the earthquakes occur beneath the water cover, but are felt on the islands, only the most significant are felt sufficiently widely to permit a reasonable macroseismic solution. Unlike the other regions where further research stands an excellent chance of unearthing additional reports of felt seismicity, the chances of this situation arising would be relatively small in the Caribbean. Therefore, the inclusion of single island reports would seriously distort the pattern of seismicity in the pre-instrumental period when settlement in the islands was extremely uneven.

A review of historical seismicity in México was a special undertaking of the project. Led by Gerardo Suárez, (UNAM) this activity included a visit by historians to the archives in Seville, Spain, and studies of pre-Columbian glyphs in a four-pronged effort to carry out a thorough study of pre-1898 seismicity in México. The first phase of the project has led to a verbatim publication of the portions of historical documents relevant to seismicity (Suárez et al, 1995). The second phase is the seismic interpretation of these historical records, which to this point has involved a study of only the major events (about 20 of them). The third is ongoing co-operation with anthropologic institutes in México (such as the Centro de Investigaciones y Estudios Superiores en Antropologia Social) to gain further insight into pre-historic earthquakes through the study of glyphs of ancient native populations. The fourth is an ambitious undertaking, predicated in part on the results of the first three phases, that will study the social and economic effects, both historic and current, within México. This latter study will clearly extend far into the future and will depend heavily on the availability of the Gerardo Suárez, who now occupies a senior position within the hierarchy of UNAM.

(b) Instrumental data

The ISC catalogue contains two types of epicentre record. Primary records are the solutions adopted by the ISC as the most reliable available. These are identified by and asterisk (*) in column 1 of an 80-column record. Any other symbol in this column (usually, but not always, a blank) indicates that the record is secondary to a preferred solution to the event. Prior to January 1, 1964 the epicentres were computed in a variety of ways and are of extremely variable reliability. Subsequently, the ISC either computed its own epicentres using contributed arrival times and global average travel time tables (Jeffreys and Bullen, 1939) or accepted epicentre solutions from other agencies. Epicentres of the first type are identified by the code ISC in columns 2-4 of the epicentre records. Epicentres contributed by other agencies are identified by the code for the particular agency given in Appendix IX.

The regions and agencies involved in this project contributed their data in their particular formats - mostly the SISRA format. These were converted to the ISC format as the first step in compiling the project catalogue. Many of the solutions contained in these catalogues have been re-worked within the regions using improved methodology or information. As these solutions were given priority over those provided by central agencies such as the ISC, we believe there is an overall improvement in the quality of the catalogue. The use of these local and regional solutions has also resulted in a greater number of events in the project catalogue when compared to that of the ISC. We believe this increase is mainly due to a larger number of solutions computed by local sources.

While the project participants believe this catalogue is a substantial improvement over other similar efforts available for the project area, it is by no means the last word. We would be very disappointed not to see better versions in the future.

Merging of sub-catalogues

The general philosophy of assembling the project catalogue adhered strictly to the guidelines laid down by the Steering Committee. Regional and local catalogues are believed to be more reliable because they are more likely to have taken account of local knowledge and to have used local travel-time tables. This coupled with the fact that most of the catalogues were reviewed and re-worked where necessary as part of the project lends further credence to this policy. The principal problem with creating a catalogue in this manner is the presence of multiple solutions to the same event. This is a common occurrence in the boundary zones between the four regions (normally those responsible for compiling the regional catalogues have resolved this question internally) and preoccupied the time and the attention of the Geophysics Commission. This problem is exacerbated when the regional and ISC catalogues are merged.

Software was developed which among others dealt with this problem (Tanner et al, 1993). The catalogues were first placed in chronological order and then merged. The merged catalogue was then searched for pairs of events that fell inside of specified space and time windows. Each set of apparent duplicates was examined visually and a decision taken as to which event(s) should be included as primary in the final catalogue. This time consuming and exacting process was repeated for each catalogue merged leading to a final catalogue of some 115,000 primary and secondary events (where a regional solution was an exact duplicate of an ISC event, the ISC event was relegated to a special file which was kept for a reference in the event subsequent analysis required further checking). Generally, highest priority was given to regional solutions, but there were exceptions based on the number of arrival times used in a particular solution (for example, a local solution with say ten arrival times was regarded as secondary in situations where the ISC solution was based on several times the number of arrivals). This occurred infrequently, but just often enough to warrant special attention. ISC solutions received second priority and the lowest priority was given to events reported only by large and small aperture arrays (e.g., LASA, NORSAR) located completely outside the project area and by international agencies (e.g., in Moscow and Peking) which used arrival times from continents other than Latin America and the Caribbean. In some cases the final choice was difficult and often reached by reference back to the agencies involved in the original solutions. Therefore, a decision was taken to include secondary solutions in the catalogue but identify them with a blank in column 1 so that they would not be used in the computations but would be available for others who might wish to reverse our decision. All other rejected solutions were retained in separate files.

The MANAGE software system

This is the primary vehicle used to merge the various catalogues. Originally intended to facilitate the merging process, it gradually grew to include routines to check catalogues for order and sort them if out of order, check date and time entries for errors, check agency codes, retrieve data from the catalogue in at least two formats, bring up a screen display showing the locations, magnitudes and depths of events as desired, convert magnitudes in the original catalogue to moment magnitude and so on. Two versions of the computer programme are available (one with the screen plot included and one without it). Written in FORTRAN executable object files are available to interested users. IDRC has requested that we not release the source code because of potential problems with users wishing help in making changes. A listing and short description of each of the routines is given below.

(i) The MAIN Programme

Serves as an organizer which asks the user which action is to be undertaken and directs the programme to the appropriate subroutines.

(ii) The COUNT subroutine

Originally intended as an aid in checking results obtained with other subroutines, this subroutine has been left because it provides a useful summary of the number of events, both primary and secondary, in the catalogue.

(iii) The MERGE subroutine

This subroutine merges catalogues which are presumed to be in chronological order. A user identified primary catalogue is given priority over a (user identified) secondary catalogue with the result that entries in the secondary catalogue with the same identifier (date and time) as those in the primary catalogue are placed in a special duplicate catalogue in the event further analysis is required. This subroutine carries out several checks to ensure the integrity of the data and gives a short summary of the merging operation at its conclusion.

(iv) The TIME and SPACE WINDOW subroutine

This subroutine:

(a) checks a catalogue for duplicate identifiers prior to a merge operation, and

(b) places user specified time and space windows on the file to aid in the search for possible duplicate solutions to the same event.

Each of these routines writes a file of information, consisting of pairs of events meeting the limits specified by the time- and space-windows, which can be printed out to aid the user in deciding which events to identify as primary or secondary. The output files have been laid out for use on most laser printers, but can be used on ink jet or pin-based printers with relatively little inconvenience (although there may be some rolling of the headers from page to page). The choice of action is left to the user.

(v) The SPLIT subroutine

This subroutine will divide any given catalogue into sub-catalogues of equal or time-based length. As the project catalogue is nearly 10 mbytes in length this subroutine is useful in compiling sub-catalogues of more manageable length for editing and listing of data and display of data to mention two uses.

(vi) The COMBINE subroutine

Combines catalogues which are presumed to be consecutive in time. In situations where catalogues are not consecutive, the MERGE subroutine should be used. The MERGE subroutine is more general and could be used in place of this much simpler subroutine.

(vii) The SELECT subroutine

This subroutine is capable of selecting events on the basis of location, depth, magnitude and time (to a limit of a period of a day) in any combination. Two files may be printed out which list the selected events in either the original ISC format or a special "shortcat" format containing the originating agency, the identifier, location, magnitudes and responsible agencies and depths. The output can be listed on a laser printer for reference and the file written by the subroutine further processed to produce a plotted file on whatever device is locally available.

(viii) The GENPLOT subroutine

This subroutine produces a screen plot of data selected using the SELECT subroutine. The screen display can be used to classify by depth and magnitude. A small legend accompanies the screen plot.

(ix) The CHECK AND SORT subroutine

This subroutine is used to check a given catalogue for chronological order and sort it should it be found to be out of order. Lengthy catalogues may be slow on some computers if badly out of chronological order.

(x) The FORMAT CHECK subroutine

This subroutine is used to check the format of catalogues for the ISC format only. Events out of format are identified for further action as appropriate.

(xi) The AGENCY CODE subroutine

This subroutine lists and sorts the originating agencies for both the epicentre determination and the magnitude determination in descending order of frequency.

(xii) The MOMENT MAGNITUDE subroutine

This subroutine converts source catalogues to moment magnitude catalogues using procedures described later in this chapter.

Some excellent software is also freely available from SRU/UWI in Trinidad through Mr. Lloyd Lynch whose address and telephone number are given in Appendix VII. Known within the project as the UCHE system (from the first name of the programmer) and written in BASIC this programme possesses many of the capabilities of MANAGE. It has been used extensively with the project for conversion between the two formats (ISC and SISRA) adopted by the Steering Committee. For those with older models of the PC computer who might wish to manipulate catalogues from different sources, we recommend the use of this useful software (as we do for those with more recent models).

There is of course other software that has been used by the participating agencies not only for catalogue assembly, but also for other purposes related to the catalogue and seismic hazard estimation in general. We also note that extensive use has been made within the regions of software freely available through the USGS. Individuals interested should check with the regional agencies or the USGS to get an up-to-date information regarding freely available software.

Measures of earthquake size

One aim in the compilation of this catalogue has been the description of the size, on a uniform scale, of as many earthquakes as possible to provide a good basis for the comparison of seismicity from one region to another and the estimated levels of ground motion generated by earthquakes at various locations from region to region. The preferred descriptor among seismologists is seismic moment, M_o, but the general public and the engineering community have become accustomed to the quantity magnitude as a measure of earthquake size. In addition, almost all existing empirical relationships used to predict earthquake ground motion require that earthquake size should be described as magnitude. Seismic moment can be expressed as a magnitude using the formula derived by Kanamori (1978)

$$M_w = \tfrac{2}{3}\log_{10}M_o - 10.7 \qquad (1)$$

where M_w is the moment magnitude and the units of seismic moment are dyne-cm.

According to Kanamori (1978), moment magnitude is equivalent to surface wave magnitude, M_s, if M_s is less than about 8.0 and to local magnitude, M_l, if M_l is less than about 7.0. For earthquakes with magnitudes greater than these values the respective magnitude scales begin to saturate and magnitude, as conventionally measured from the amplitude and period of seismic waves, is no longer a reliable predictor of seismic moment.

Unfortunately the number of direct measurements of M_o for this project area is very small. For the period up to 1977 almost all estimates of seismic moment were from geodetic estimates of the quantities μ, A and $\bar{d}$ in the equation defining M_o (Aki and Richards, 1980),

$$M_0 = \mu A\bar{d} \qquad (2)$$

where μ is the modulus of rigidity, A is the area of the rupture and $\bar{d}$ is movement in the direction of slip. In its original form the catalogue contained less than 50 such direct measurements of M_o or the equivalent quantity M_w. The most up-to-date global compilation of these estimates is that of Pacheco and Sykes (1992) who list direct seismic moment estimates for 37 earthquakes in the project area for the magnitude range $7.0 < M_s < 8.0$ during the period up to 1977.

Many of these magnitudes were originally determined by Gutenberg and Richter (1954). However, many of their determinations have been subsequently modified, notably by Abe (1981, 1984) and Abe and Noguchi (1983a, 1983b). Pacheco and Sykes (1992) further modified the events in the range given above and noted that these determinations are now in accord with the procedures used for determination of M_s by the USGS and ISC. We have used mainly these re-determinations made by Pacheco and Sykes (1992), but have included a number of re-estimations of magnitudes within this particular range by a number of seismologists from the project area during the compilation of the revised catalogues for their respective regions. These sources are included in Appendix IX.

For the period 1977-1992 a much more comprehensive set of seismic moment determinations is available through the work of Dziewonski and colleagues (Dziewonski et al, 1982). They have determined seismic moments for a large number of earthquakes by the Centroid Moment Tensor (CMT) method. Their results have been published in the journal *Physics of the Earth and Planetary Interiors* and are available on magnetic tape as the Harvard University Centroid Moment Tensor Catalogue (CMT). This catalogue provides direct measurements of seismic

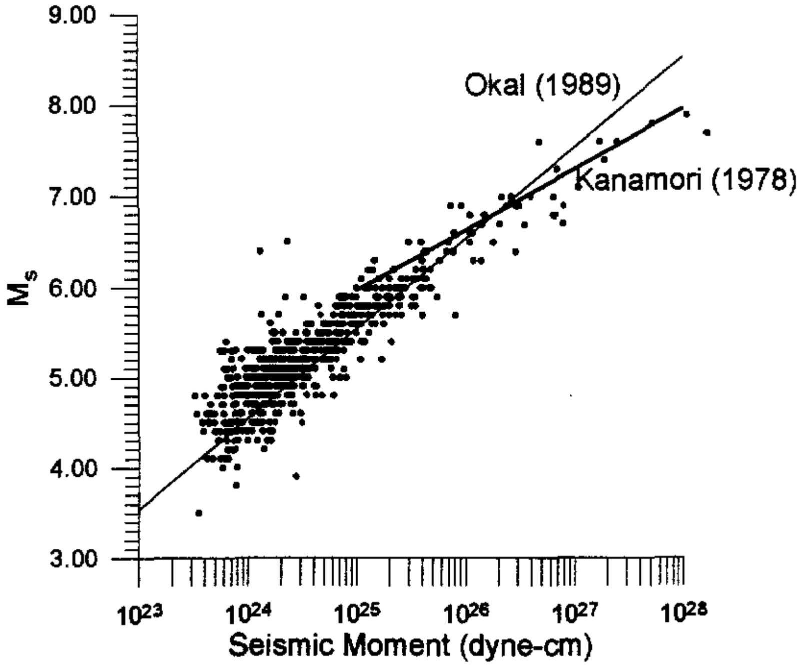

Figure 1. Relationship between seismic moment and surface wave magnitude. Note the comparison between actual data and the two theoretical relations shown.. This is an attestation to the quality and consistency of the estimation of surface wave magnitudes throughout the project area.

moment in our project area for 1,185 earthquakes. We have identified reliable determinations of M_s, that is determinations made using the Prague formula (Vanek et al, 1963), for 613 of these events. These have been plotted against log M_o (Fig. 1) to provide a basis for converting M_s to seismic moment.

Fig. 1 shows that the Kanamori relationship fits the data well at the upper end of the scale ($M_o > 10^{26}$ dyne-cm) but for the values below that a relationship derived theoretically by Okal (1989)

$$\log_{10}M_o = M_s + 19.46 \qquad (3)$$

provides a much better fit. For earthquakes used in the catalogue with estimates of M_s greater than 6.6 we have used equation 1 to estimate seismic moment. For earthquakes with magnitudes $M_s \leq 6.6$ conversion has been made using the relationship

$$M_w = (2/3)M_s + 2.34 \qquad (4)$$

derived from a combination of equations (1) and (3).

By far the most common magnitude scale used in the catalogue is the body wave magnitude, m_b. In principle it should be possible to establish similar theoretical and empirical relationships by which M_w can be estimated from m_b. Unfortunately any such relationships are less precise than that for M_s. In this circumstance the estimation of M_o from m_b can be approached in two ways.

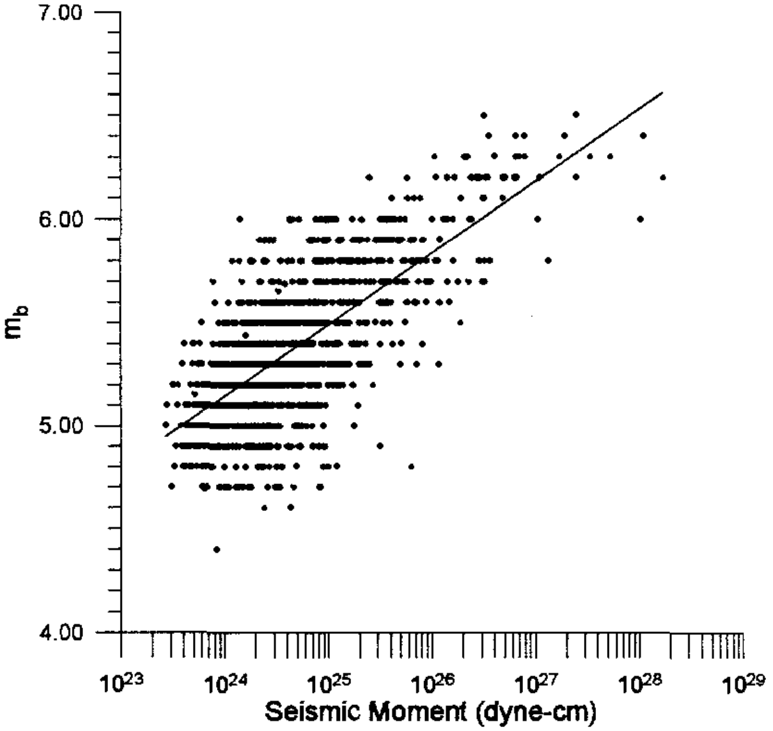

Figure 2. Comparison of seismic moment and body wave magnitude for over 100 earthquakes.. The straight line fit shown has been computed using all events.

The first is to proceed as we did with M_s: to plot M_o against m_b for those events for which there are simultaneous measurements of both quantities. In Fig. 2 we have plotted m_b against $\log_{10}M_o$ for 1189 earthquakes in the project area. Although there is a linear trend, there is much more scatter of individual values about the best fitting line and the effect of saturation of the body wave magnitude scale can be seen clearly. For values of M_o less than about 10^{26} dyne-cm the best fit relationship is

$$m_b = 0.35\log_{10}M_o - 3.17, \tag{5}$$

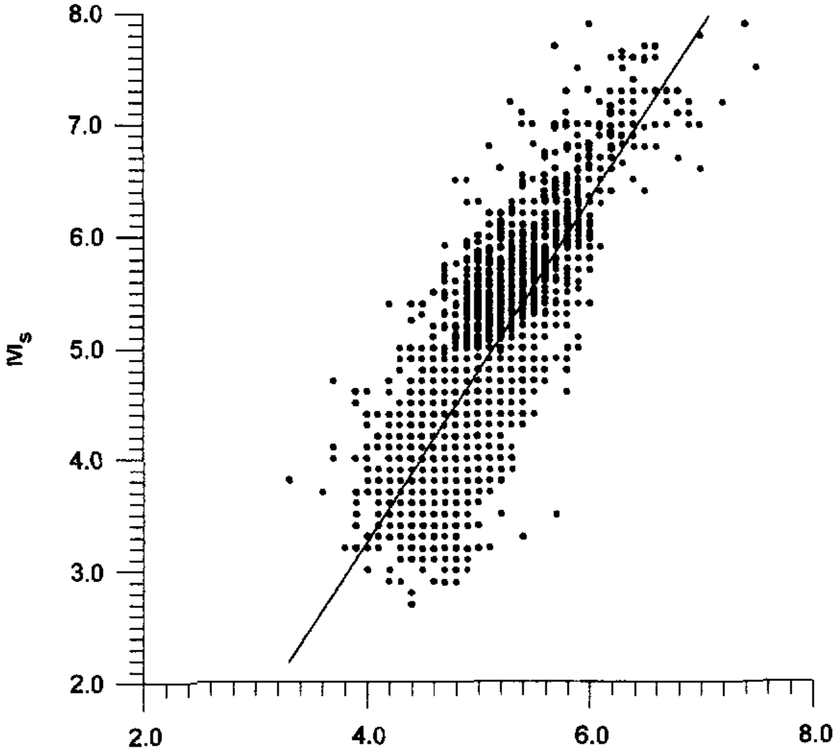

Figure 3. Relationship of surface wave magnitude to body wave magnitude for 2993 events scattered throughout the entire project area.

but the fit is extremely poor and a wide range of constants could be substituted in equation 5 without changing the quality of fit substantially.

The second method of estimating seismic moment from m_b is first to convert m_b to M_s using an empirically derived relationship(s) and then derive M_o from M_s using the methods described above. Fig. 3 shows M_s plotted against m_b for 2993 earthquakes in the catalogue for which there are simultaneous measurements of both quantities.

The best fit line through all the data points is

$$M_s = 1.54m_b - 2.89 \qquad (6)$$

with a linear correlation coefficient of 0.82. The scatter about the linear regression is of the order ±one magnitude unit and the linear fit is worst at the extremes of the fitted line. Again a fairly wide choice of constants in equation 6 is possible without any significant improvement in the quality of fit. Fig. 4 illustrates yet another attempt to clarify the relationship between M_s and m_b. This diagram illustrates that the linear relationship between the two magnitudes holds best in the range $4.6 \leq m_b \leq 6.2$. Within this range the linear relationship is

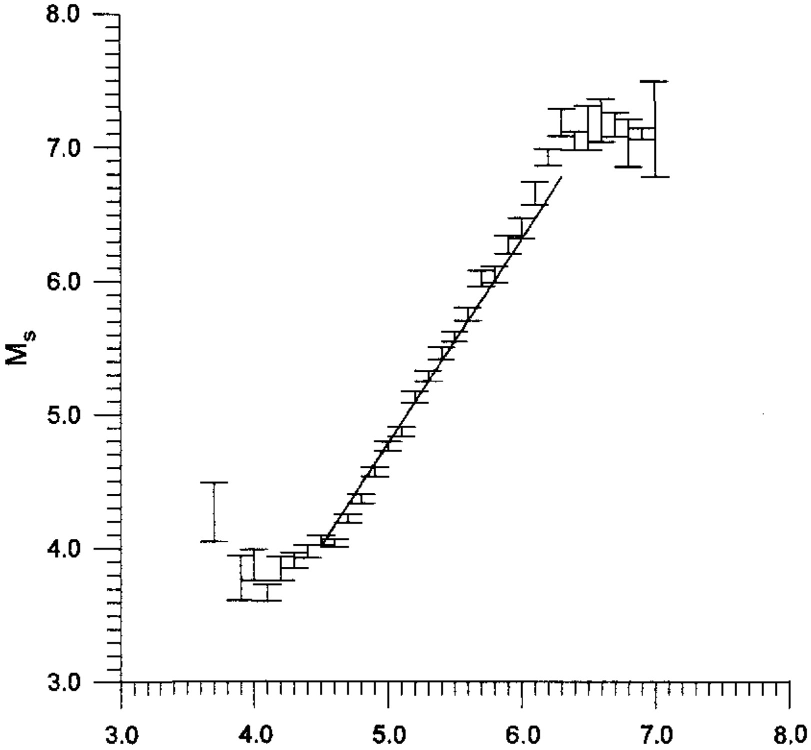

Figure 4. The relationship of surface wave magnitude represented by standard error bars to body wave magnitude. Although the range of magnitudes within which there is a good straight line fit is limited, the definition of this line is unequivocal.

$$M_s = 1.74m_b - 3.95. \qquad (7)$$

Outside this range the two quantities hardly seem correlated at all. If the regression is performed in the opposite sense - i.e., with M_s as the independent variable - the resulting relationship is

$$m_b = 0.36\,M_s + 3.35. \qquad (8)$$

The main conclusion to be drawn from this part of our analysis is that body wave magnitude, in our project area at least, is a poor indicator of earthquake size.

Nevertheless, we need some way of estimating the seismic moment of events for which the only information is an estimate of m_b, since these events make up about 63% of those for which there is any magnitude information available at all. Although the three possible conversion methods appear to be radically different, they give results (M_w) which are within ±0.5 units in all cases. We have used equation (7) to convert m_b since it is based on the most comprehensive data set and gives about as clear a result as can be expected.

There remain a number of earthquakes for which only one magnitude is reported, usually M_L or M_l. Where M_l is known to have been calculated using the original method (Richter, 1957), we have assumed it is equivalent to M_w.. For other scales where the relationship with either m_b or M_s (Shepherd and Aspinall, 1983 (Lesser Antilles); Rojas et al, 1993, (Central America)) is known, the relevant conversion formulae have been used where appropriate. Where no conversion formula is known, the records in the catalogue have been excluded form this process.

Finally, we would like to note that the equations given above are those actually used in the compilation of the moment magnitude catalogue. One of us (JBS) has undertaken to update these equations when new data from the ISC are added to the original catalogue. The changes of the coefficients of the straight line fits are expected to be relatively minor and of no significance for this work. Anyone interested in following up on this particular aspect should contact JBS directly.

Hierarchy for the estimation of seismic moment

From the above discussion the order of priority for the estimation of seismic moment is therefore:

(i) M_o from geodetic measurements,

(ii) M_o from the spectrum of broad-band, digital displacement seismograms,

(iii) M_o from the Centroid Moment Tensor,

(iv) M_w from M_s (Prague formula),

(v) M_w from M_s (other methods),

(vi) M_w from m_b,,

(vii) M_w from other magnitude scales.

Following this hierarchy we have estimated the seismic moments for over 48,000 events or about 46% of those in the catalogue. Table 1 shows the proportions of each type of magnitude

Table 1
Original magnitude sources for estimation of seismic moment

Magnitude type	% of total events	% of total moment release
m_b	63.1	0.6
M_s	12.1	38.4
Other	22.2	negligible
M_w	2.6	61

determination. Although m_b and other determinations account for over 85% of the total number of earthquakes, they represent less than 1% of the total moment release.

In fact, over 95% of the moment release by events in the entire catalogue corresponds to the ten largest earthquakes and nearly 60% corresponds to the single largest earthquake. In terms of major tectonic process the events for which we have imprecise determinations of seismic moment are of negligible significance. They may, however, be extremely significant for seismic hazard assessment.

Macroseismic Data

One of the major objectives of the catalogue phase of the project has been improvements in the historical portion of it. This particular aspect was singled out for special funding in the budget and visits were carried out to European archives as well as those in the region.. At the moment over 2,600 entries in the catalogue have resulted from these activities. The distribution of these events with time is given in Table 2.

Table 2
Macroseismic events for the period 1471-1899

Period	Number of events
to 1499	1
1500-1599	75
1600-1699	108
1700-1799	480
1800-1899	1,959

Magnitudes, where available, have been assigned by a variety of methods based on felt area and/or maximum intensity and probably correspond to M_w to the nearest half integer. At its current state of development, this portion of the catalogue can not be used to establish recurrence rates for earthquakes, but it can be used as a guide to the maximum sizes of earthquakes experienced in the historical period in the project area. As a point of interest, we will compute the maximum ground acceleration experienced throughout the entire period of the catalogue at any point in the project area due to a single earthquake. While this value is not probabilistic it does cover the period of the catalogue (about 500 years), which is about the same as the return period for the probabilistic estimates of seismic hazard based on a 10% chance of exceedance in 50 yr.

Instrumental data

The first earthquake epicentres estimated from instrumental data in this project area occurred in 1898. From then until June 30,1994 the catalogue, after elimination of multiple solutions to the same event, contains estimates of epicentre coordinates for nearly 115,000 events. All of the statistical analysis which follows has been carried out on the instrumental portion of the catalogue only. For convenience we have taken the instrumental period of the catalogue as beginning in 1900. This excludes a very small number of nineteenth century earthquakes with instrumental epicentres and includes a small number of twentieth century events for which the data are entirely macroseismic.

Reconciliations with local authorities were necessary throughout the lengthy process of verifying the project catalogue. A number of problems with the catalogue for Central America put together in Norway were resolved quickly and effectively from our end of the operation. Much the same was true in the case of the Caribbean and South America. Only one or two minor problems were experienced with the Mexican catalogue. This is a tribute to the skill of our regional counterparts and their knowledge of seismicity within their respective regions. The result, we believe, is perhaps one of the best catalogues of its kind in existence.

We reiterate our opinion that the quality of work throughout the entire region was of uniformly high quality, if the agreement between the practical and the theoretical in the case of M_s can serve as reliable evidence. The difficulties we experienced with m_b are more a problem with the quantity itself and its definition rather than with the quality of the work. We have no doubt these estimations were pursued with the same diligence as was the case for other magnitude estimates.

Finally, we would like to emphasize that results of our analysis of the data in the catalogue have been based on a study of events for the entire project area and that we might expect different conclusions from a similar analysis of the catalogues for any of the regions.

Data completeness

No attempt has been made to assess the completeness of the macroseismic data. For the instrumental data, the periods for which the catalogue can be regarded as complete depends both on the magnitude range considered. and on geographic location within the project area. We have made estimates of the completeness of the whole catalogue to determine whether it provides a reasonable basis for quantitative probabilistic seismic hazard assessment. The basis for most of our conclusions can be seen in Fig. 5 which shows the annual number of events in the catalogue from 1900 to 1993 classified by magnitude.

A number of methods have been suggested to test the completeness of catalogues. Most of them are based on the assumption that earthquakes are randomly distributed in time, that is, the rate of occurrence of earthquakes of magnitudes greater than a stated value follows the laws of the Poisson distribution. In detail, this assumption is clearly violated by the occurrence of aftershocks and possibly by the existence of seismic gaps, but it may be a reasonable assumption to make about the rate of occurrence of earthquakes over a large project area such as is the case here. The most widely used test of completeness would seem to be the so-called Stepp test (Stepp, 1972; Bollinger, 1973; Nuttli, 1974). Here, the standard deviation (σ) of the estimate of the mean rate of earthquake occurrence (λ) for a given magnitude range is plotted against time on a log-log graph.. The data are considered to be complete so long as the graph follows a linear trend. From

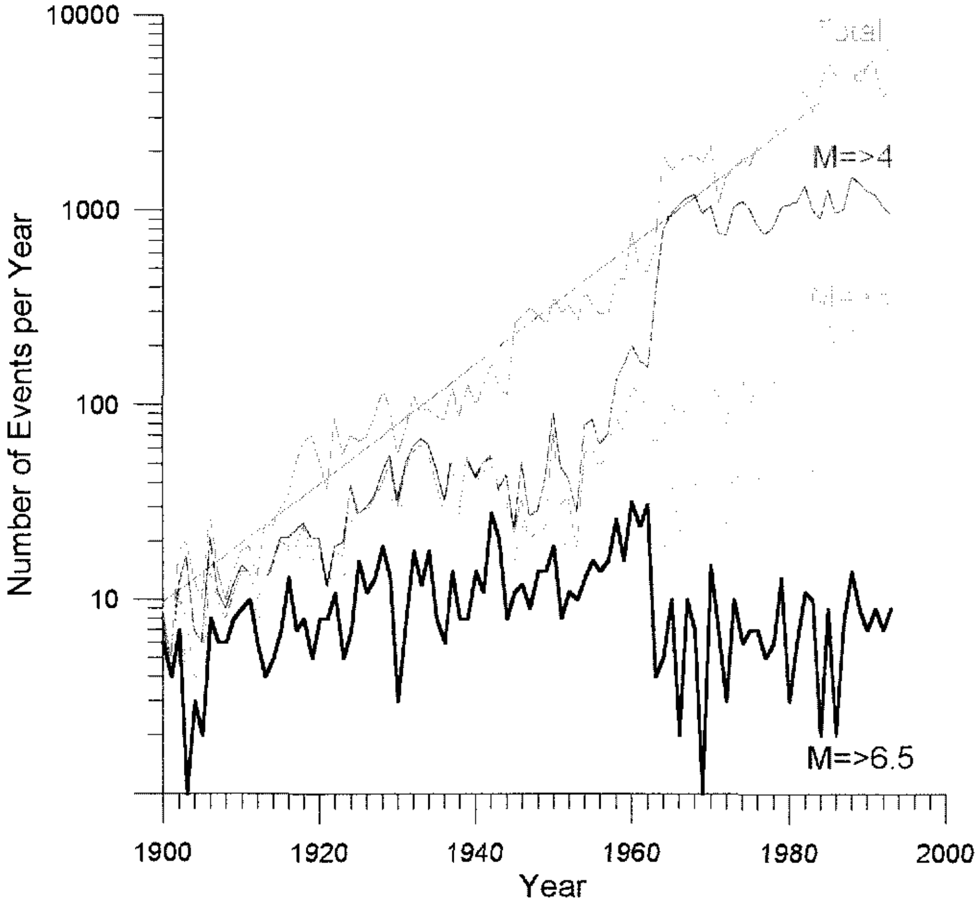

Figure 5. Annual numbers of earthquakes from 1900 to 1993 classified by range of magnitude. The results of this diagram have been used to estimate periods of completeness of events in the catalogue.

the properties of the Poisson distribution the variance of the estimate of the mean is equal to the mean itself and the standard deviation of the estimate of the mean is

$$\sigma = \sqrt{\lambda / T}\,.$$

Plotting σ against T against logarithmic axes is therefore exactly equivalent to plotting λ against T with the axes rotated through 30^0. The use of logarithmic axes and cumulative totals introduces implicit smoothing which generally appears to exaggerate the period for which the data are complete.

A more straightforward test of completeness is based simply on the constancy of λ. We begin with an assumption that is based on a knowledge of the distribution and effectiveness of the global and regional seismograph networks rather than on the numbers of data. This assumption is that all earthquakes of magnitude 5.75 (M_w) and greater can now be detected anywhere within the region. We assume further that this has been the case at least since 1964 when the WWSSN became fully effective and the ISC began to publish regular bulletins. On the basis of these assumptions it can be concluded from Fig. 5 that the data for $M_w \geq 5.75$ are complete back to about 1930 since the annual numbers for this magnitude range are approximately constant back to this date.

We assume further that the rate of occurrence of earthquakes at any magnitude range is governed by the Gutenberg-Richter (or Ishimoto-Iida) relationship

$$\log N = a - bM\,. \tag{9}$$

If this is so then, for any magnitude range less than 5.75 for which the data are complete the relevant curve on the graph should maintain a constant distance from the curve for $M_w \geq 5.75$. On this basis we conclude from Fig. 5 that the data are complete for $M_w \geq 4.0$ from 1964 onwards. Moving back beyond 1964 the line representing $M_w \geq 4.0$ rapidly converges with the lower line indicating that the data are incomplete at this magnitude level. This conclusion is not surprising because, as has already been mentioned, a discontinuous improvement in the efficiency of both the regional and worldwide seismograph systems occurred in 1964.

We also see from Fig.5 that the curve labelled M≥6.5 seems to be complete back to the very early 1900s, if no particular significance is attached to the sudden drop in level, which has been maintained until 1993, that took place in the early 1960s. No unequivocal explanation can be offered for this drop in frequency of occurrence which also seems to have taken place to a lesser extent in the case of events larger than 5.75. It is possible that this shift could coincide with some re-calibration of networks within the region to match the results contained in the reports of the (then) relatively young WWSSN. It is also possible that the pre-1960 seismicity might be an "anomalous high" and that the post-1960 seismicity "anomalously low" because of the enormous amount of stress release due to the large Chilean earthquake of that year. Whether the stress release hypothesis could be applied to the entire project area is a topic for debate. Whatever the explanation for this shift in the annual numbers for large events, the conclusions on completeness appear to be unaffected.

The total annual number of earthquakes reported within the whole region increased from 1900 to about 1984 at a rate which closely fits an exponential (the rate of increase on the curve labelled "total" in Fig. 5 is more or less linear up to about 1984). Two comments need to be made on this curve. First, it does not indicate a real increase in the rate of earthquake occurrence but simply illustrates the continuous improvement in efficiency of seismograph networks within the project area and globally. Second, the continuous increase in the number of events to 1984 is not indicative of the lack of completeness before this date, but is more likely a manifestation of the improved ability to assign dimensions to events of magnitudes less than 4.0. This latter conclusion would appear to be supported by the curve for events of magnitude 4 and greater.

Although not shown here, a comparison of the annual rate of occurrence of earthquakes for our catalogue to that for the ISC clearly shows that our decision to favour local solutions has led to a modest increase in the number of events recorded each year, particularly in the mid-years of the period covered in Fig. 5. This might be expected with an emphasis on local solutions.

Conclusions about completeness

Duplicate events have been eliminated from the instrumental part of the catalogue, but because of uncertainties surrounding dates and locations, it is possible that some duplicates remain in the macroseismic catalogue. We have examined a number of methods for completeness and have concluded that the straightforward and relatively simple approach embodied in Fig. 5, gives reasonably reliable results. Our conclusions regarding completeness are given in Table 3. Within the regions and local areas where the coverage is particularly good the periods of completeness may be longer and the magnitude limits lower. The numbers given in Table 3 reflect our estimate of the situation in the project area as a whole.

Table 3
Estimated periods of completeness by magnitude

Range	Period of Completeness
$M_w \geq 7.5$	1900-1993
$M_w \geq 5.75$	1930-1993
$M_w \geq 4.0$	1964-1993

Data presentation

Graphical presentation of catalogued seismicity in a way that carries the maximum amount of information with the minimum distortion presents some problems. The simplest way of presenting

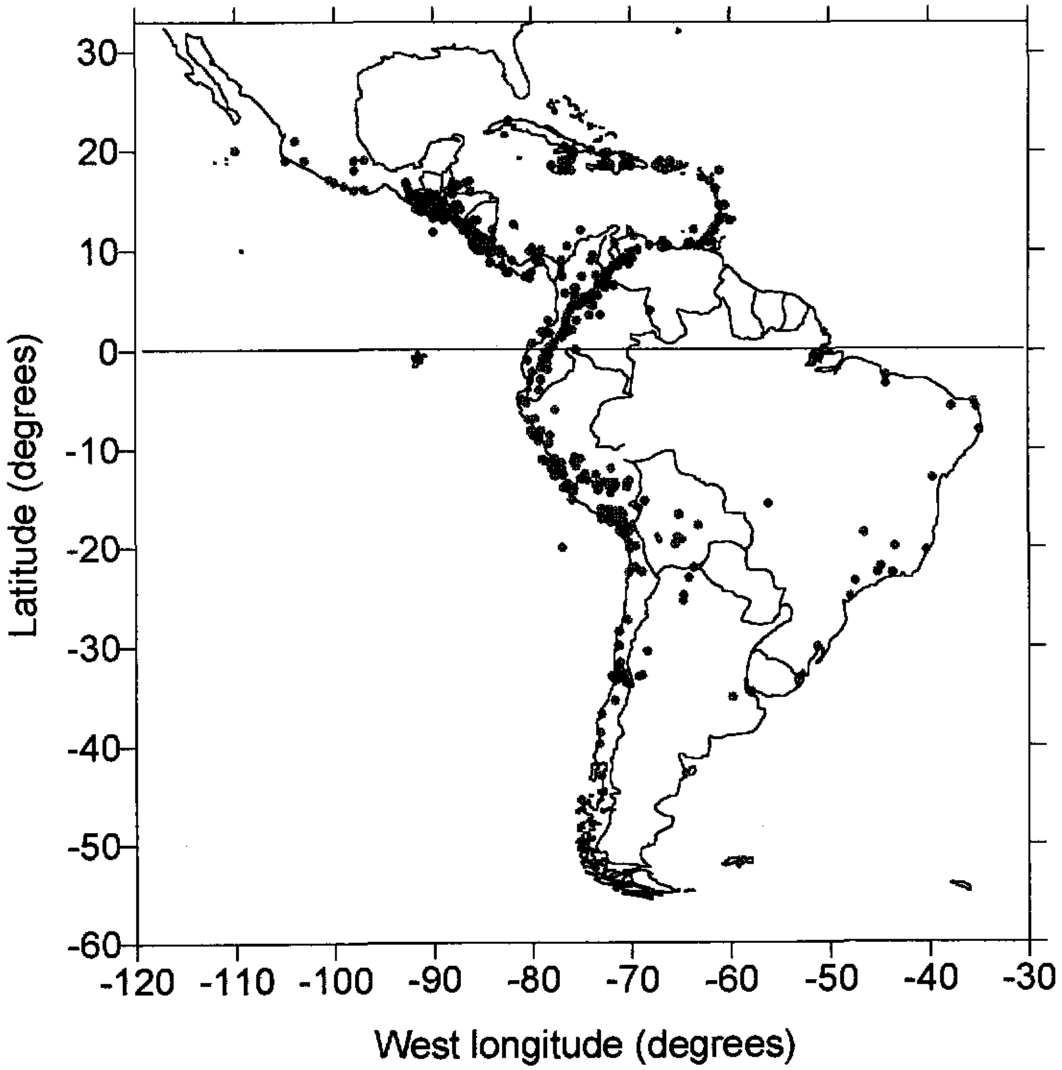

Figure 6. Distribution of earthquakes in the catalogue for the period 1471-1899. There are 2,623 macroseismic events plotted in this diagram.

the data is to plot each earthquake as a single dot with no weighting for earthquake size or code for depth such as is the case for Figs. 6, 7 and 8 which are snapshots of the distribution of seismicity for three periods within the time span of the catalogue.

Fig. 6 shows the distribution of the more than 2600 macroseismic (prior to 1900) events in the project catalogue. As expected no information is available regarding events taking place in oceanic areas, but the land distribution is a manifestation of what might be expected in a project area in which the seismicity is dominated by events associated with a large and active subduction zone along the west side of the continent. The reader should also be aware of the influence of the distribution of population centres regarding reports of felt seismicity and that the number of these reports increased with population density. Therefore, the number of seismic interpretations of historical records was greatest in the nineteenth century.

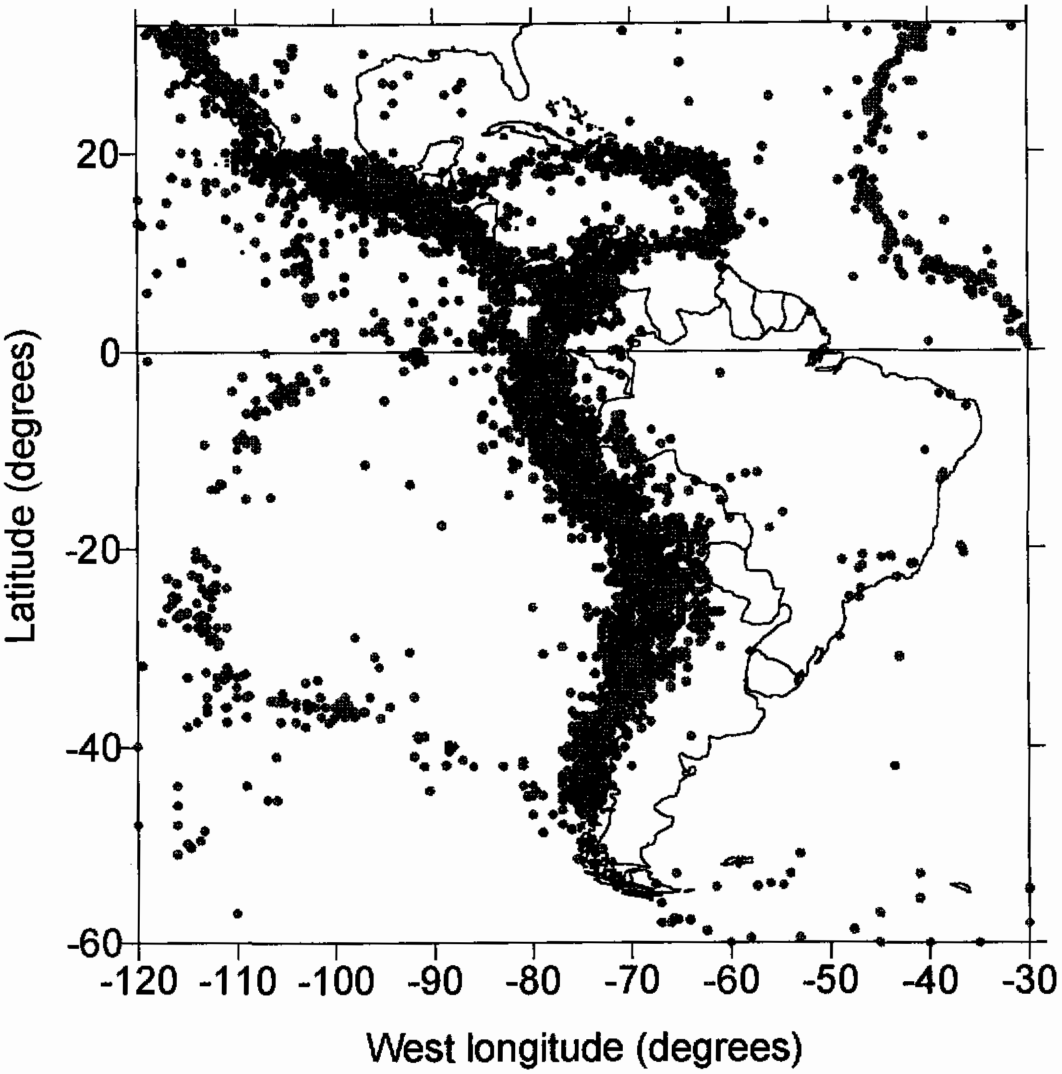

Figure 7. Distribution of earthquakes in the catalogue for the period 1900-1963. There are 10,049 events plotted on the map.

Fig. 7 covers that portion of the instrumental period between 1900 and the creation of the ISC in 1964. As might be expected the distribution and frequency of occurrence of seismicity is consistent with a project area containing an active subduction zone and offshore spreading centres. The outlines of the Cocos and Nasca Plates are evident, although nothing can be said about the rate of divergence at the spreading centres nor the rate of convergence at the subduction zone. The number of events in relation to the period covered by the diagram reflects the inadequate distribution of seismograph stations, leaving no doubt about the lack of completeness for this interval of time.

Fig. 8 on the other hand shows the distribution of seismicity in the project area following the creation of the ISC and its regular and more complete bulletins on seismicity. The distribution of seismicity leaves no doubt about the improved nature of the coverage of seismic stations throughout the entire project area. (There are locations for nearly 95,000 recorded events shown

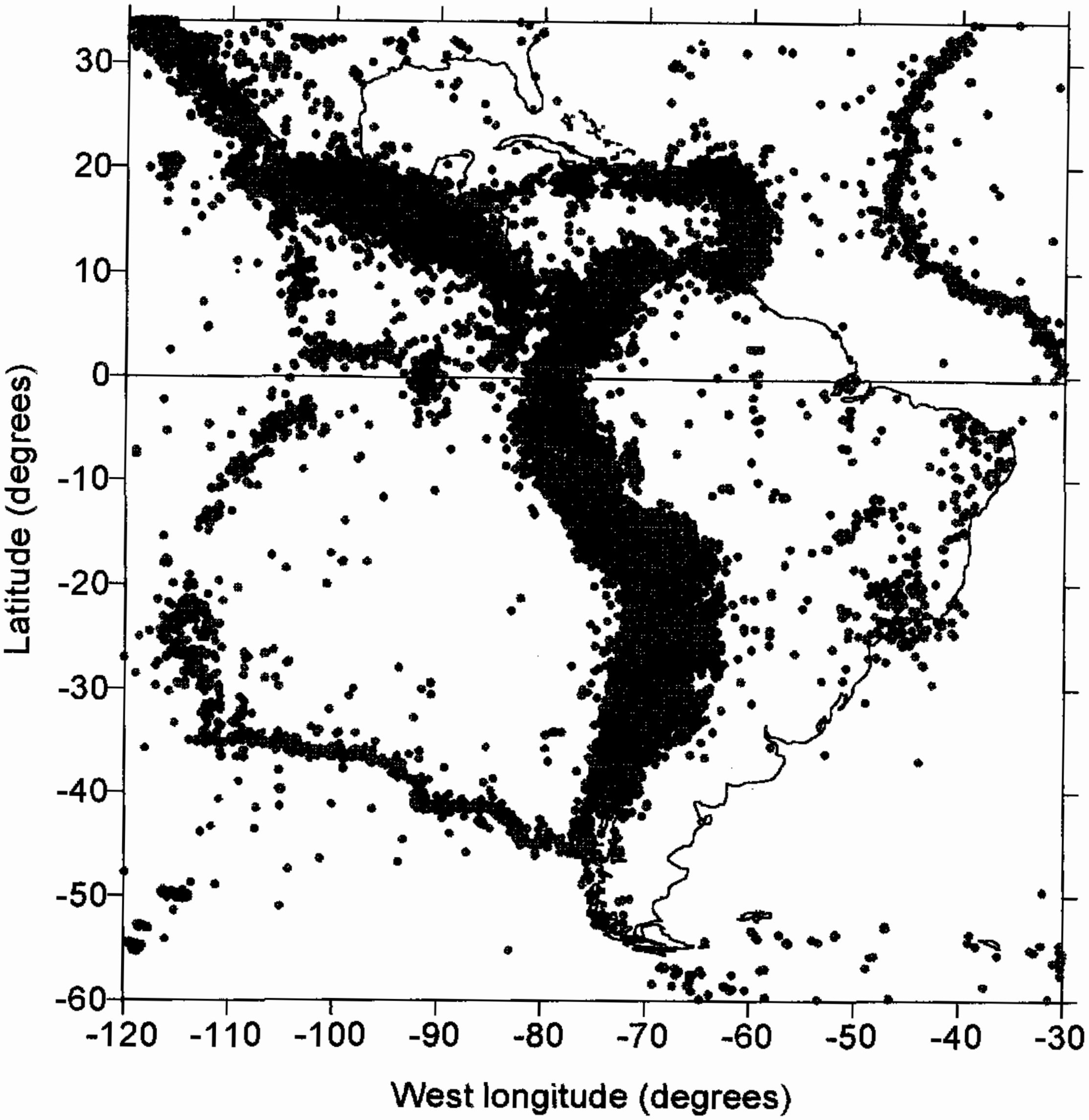

Figure 8. Distribution of earthquakes in the catalogue for the period 1964 -1994. There are 94,768 primary events plotted on this diagram.

in Fig. 8 as compared to about 10,000 recorded events in Fig. 7). The pattern of seismicity is much the same as that for Fig. 7, but with a much clearer definition of the principal features of the tectonics. The oceanic boundaries of the Cocos and Nasca plates are much more sharply shown although there are two rather large gaps in the definition of the boundary. A study as to why these occur is beyond the scope of this project, but their presence may have tectonic significance. Strikingly evident in Fig. 8 is the dominance of the subduction zone along the west coast of the continental area as the source of by far the greatest number of events recorded.

The advantage of showing the earthquakes in the project area as a dot at the location of each epicentre in the catalogue is that all areas of significant seismic activity are immediately apparent and the broad features of the tectonic process taking place can be quickly recognized (as is

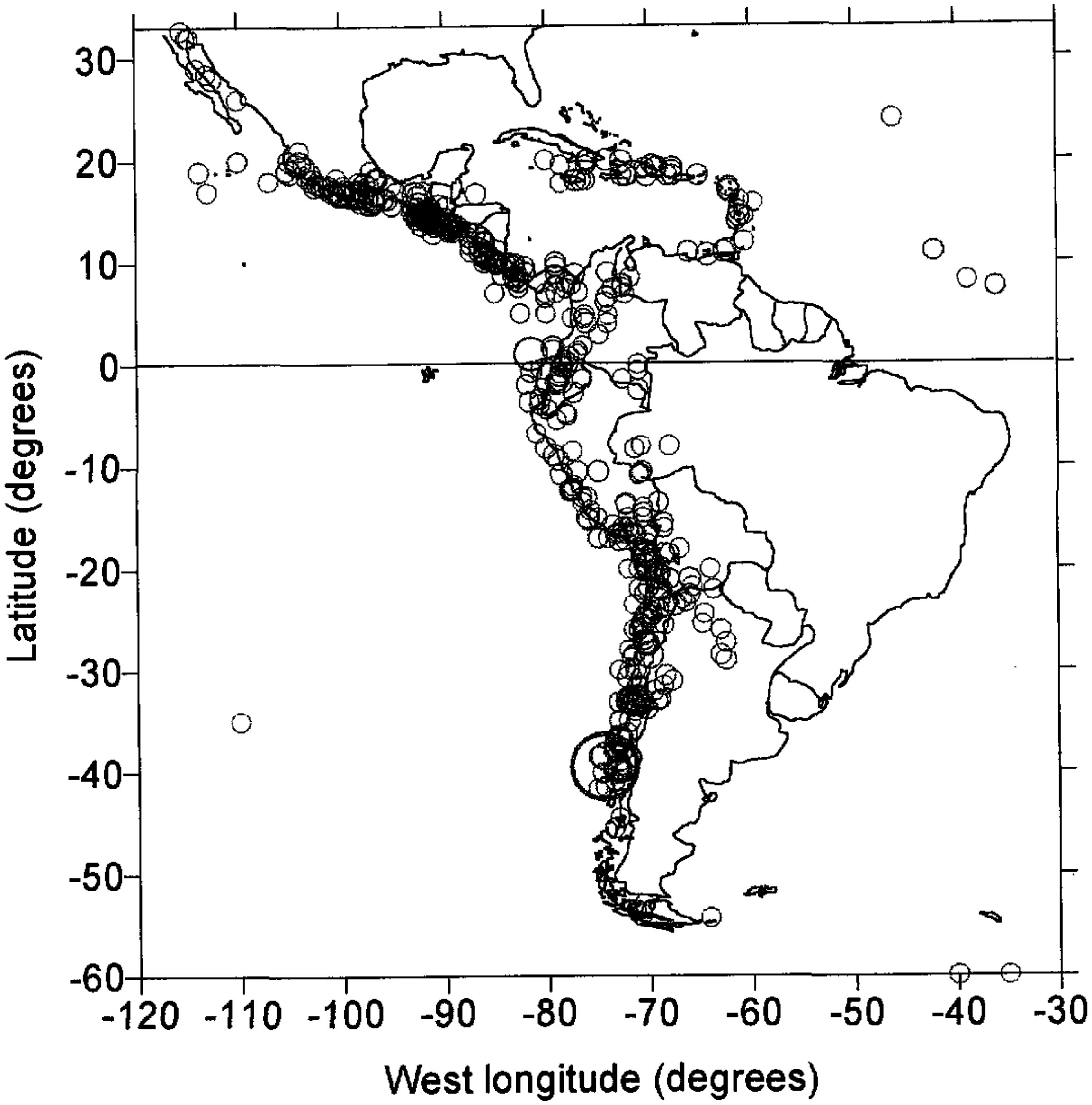

Figure 9. Distribution of earthquakes in the catalogue for which $M_w \geq 7.0$. There are 501 events represented in this diagram for which the size of the symbols is proportional to the square root of the seismic moment.

certainly the case for Fig. 8). The disadvantage is that all earthquakes receive equal weight with the result that emphasis is given to earthquake numbers rather than tectonic significance. The obvious solution of weighting symbol size according to earthquake magnitude is not easy to implement satisfactorily. From equation (1) the range in seismic moment, from the smallest events in the catalogue (about magnitude 2) to the largest (magnitude 9.5), is more than eleven orders of magnitude. In any direct weighting scheme the very few major earthquakes would completely dominate the smaller ones, which could even be lost in some proportional weighting scheme. As a compromise we have chosen to show (Fig. 9) only the events for which $M_w \geq 7.0$ because they represent by far the greatest portion of total seismic moment for the project area.. They are shown as open circles, the size of which is weighted according to the square root of the seismic moment.. For the estimation of seismic hazard none of Figs. 6, 7, 8 or 9 conveys a true picture of the effects of earthquakes on the surface. While the large events dominate the estimates of seismic hazard, there are significant contributions from smaller events.

Conclusions

The original aim of this phase of the project was the compilation of a catalogue, with multiple solutions to the same events removed, that would serve as a useful addition to the regional catalogues and which could be used to compute a reference framework for seismic hazard computed in the regions.. The word reference is used in the sense of a means of comparing seismic hazard in one region or country with that anywhere else. Subsequently, the project undertook to provide a catalogue for GSHAP and hence the conversion of magnitudes to moment magnitude wherever feasible.

Some conclusions that may be drawn at this point are:

(i) The contributions on the part of the many individuals throughout the project area in estimating magnitudes and locating the epicentres of the events in the catalogue is of good quality and consistent throughout. This is quite remarkable considering the considering the large number of individuals and agencies involved in this process and the lack of resources in many cases.

(ii) The approach for letting the data speak for themselves has served this phase of the project well, particularly during the conversion of the various magnitudes to moment magnitude - the effort to convert body wave to moment magnitudes is a good example.

(iii) The historical (macroseismic) portion of the catalogue is a vast improvement over what was previously available. However, there is still much to do, particularly in the area of the seismic interpretation of historical records.

(iv) The willingness of individuals in the regions to respond quickly when problems with the entries in the project catalogue were encountered has contributed greatly toward making this one of the best catalogues of its kind to date. Without this co-operation this catalogue undoubtedly would have suffered in terms of quality.

(v) Body-wave magnitudes seem to be more irregular if comparisons with other magnitudes are any indicator. Rather than persist with this magnitude scale, it might seem preferable to use local magnitudes when it is not possible to compute surface wave or moment magnitudes directly. Unfortunately the use of body-wave magnitudes is well entrenched in the community.

(vi) Advances in our understanding of the tectonic significance of major earthquakes will occur much more rapidly with the adoption of digital technology throughout the project area. Catalogued information, while useful in displaying patterns of seismicity, is not particularly useful in this regard.

(vii) When it comes to the use of catalogues for computing seismic hazard, the identification of problems and errors is never-ending. It is therefore unthinkable that this catalogue, with all its improvements, can be left untouched..

(viii) The periods of completeness given in Table 3 suggest that the catalogue is adequate for the computation of seismic hazard throughout the region as a whole. The conclusions as to the periods of completeness may differ somewhat in the regions and local areas where the coverage may be better or worse than the project area average.

Conclusiones

El propósito original de esta fase del proyecto fue la compilación de un catálogo del cual se eliminaran las soluciones múltiples de un mismo evento, que servirá como una adición útil a los catálogos regionales y que puede usarse para calcular un marco de referencia para el peligro sísmico calculado en las regiones. El término referencia se utiliza en el sentido de que proporciona un medio de comparar el peligro sísmico en una región o país con el de cualquier otro lugar. Consecuentemente, el proyecto tomó a su cargo el proporcionar un catálogo para el GSHAP y por lo tanto la conversión de magnitudes a magnitudes de momento siempre que fuera apropiado.

Algunas conclusiones que pueden obtenerse en este momento son:

(i) Las contribuciones aportadas por las personas en toda el área del proyecto en la estimación de las magnitudes y la localización de los epicentros de los eventos en el catálogo es de buena calidad y consistente en general. Esto es realmente notable tomando en consideración el gran número de personas y agencias involucradas en este proceso y la falta de recursos en muchos casos

(ii) El enfoque de permitir que los datos hablen por ellos mismos sirvió adecuadamente en este fase del proyecto, particularmente durante la conversión de las diversas magnitudes a magnitudes de momento - el esfuerzo de convertir ondas-de-cuerpo a magnitudes de momento es un buen ejemplo.

(iii) La parte histórica (macrosísmica) del catálogo representa una mejora sustancial respecto de la disponible previamente. Sin embargo, aún queda mucho por hacer, particularmente en la interpretación sísmica de los registros históricos.

(iv) La buena disposición de los particpantes en las diversas regiones para responder rápidamente cuando surgieron problemas con los datos en el catálogo del proyecto, contribuyó grandemente a hacer de éste uno de los mejores catálogos de su tipo a la fecha. Sin esta cooperación, el catálogo habría indudablemente sufrido en términos de calidad.

(v) Si la comparación con otras magnitudes es indicativa, las magnitudes de ondas-de-cuerpo paracen ser más irregulares. En lugar de continuar con esta escala de magnitudes, parece perferible usar directamente magnitudes locales cuando no es posible calcular magnitudes de momento o de ondas de superficie. Desafortunadamente, el uso de magnitudes de ondas-de-cuerpo está fuertemente arraigada en la comunidad.

(vi) Nuestra comprensión del significado tectónico de los grandes terremotos aumentará mucho más rápidamente con la adopción de tecnología digital en toda el área del proyecto. La información catalogada, aun cuando es útil al mostrar patrones de sismicidad, no es particularmente útil a este respecto.

(vii) Por lo que se refiere al uso de catálogos para el cálculo de peligro sísmico, la identificación de problemas y errores nunca termina. Por lo tanto es impensable que este catálogo con todas sus mejoras permanezca inalterable.

(viii) Los periodos de cobertura dados en la tabla 3 sugieren que el catálogo es adecuado para el cálculo de peligro sísmico en toda la región en su conjunto. Las conclusiones en cuanto a los periodos de cobertura pueden diferir un poco para las regiones o áreas locales, dependiendo de que la cobertura haya sido mejor o peor que el promedio en toda el área del proyecto.

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Seismic Hazard Maps

Summary

The Steering Committee of the Seismic Hazard Project - Latin America and the Caribbean - directed IPGH to compile a "five level" probabilistic seismic hazard map for the project area using the historic parametric method to compute the gridded estimates. This map would serve as a common reference to the seismic hazard maps to be produced independently by each of the regions using a computational procedure of their choosing (all but the Caribbean chose the source zone method).

The five levels of seismic hazard defined by the Steering Committee are:

- 0 - 62.5 gal - minor hazard
- 62.5 - 125 gal - low hazard
- 125 - 250 gal - moderate hazard
- 250 - 500 gal - significant hazard
- > 500 gal - high hazard

The computer programme developed by IPGH especially for the project and this assignment has the following features:

- incorporates estimated uncertainties of the earthquake parameters into the calculations using pseudo-random numbers to scale standard deviations assigned to each parameter - a normal distribution has been assumed for all parameters except those (attenuation and depth) which may generate values less than zero in which case we assumed a log-normal distribution.

- aftershock sequences have been removed from the list of earthquakes used for the calculations by the method of Davis and Frolich (1991) with a cut-off interval of seventy-five (75) "space-time" days.

- extrapolation to the required return period (474.56 yr for 10% probability of exceedance in 50 yr) has been carried out using the equation

$$\ln A = \ln A_{\max} - \alpha e^{-\beta R},$$

where α and β are constants to be estimated from the data, $A_{\max}$ is the maximum possible value of PGA at the field or target point and R is the return period. Note that when $R \to \infty$, $A \to A_{\max}$.

As directed by the Steering Committee, the computer programme has been applied under the following conditions:

- all events with moment magnitude $M \geq 4.0$ have been selected from the earthquake catalogue

- the catalogue has been assumed to be complete for $M \geq 4$during the period 1964-1993

- we chose CLIM94 for the computations from among the following attenuation relations provided by the members of the Steering Committee:
  - ORDAZ94 (Mario Ordaz of UNAM, personal communication, 1994)
  - CLIM94 (Climent et al, 1994)
  - KAUSEL94 (Edgar Kausel, Universidad de Chile, personal communication, 1994
  - WC82 (Woodward-Clyde, 1982)

- used the JB93 (Boore et al, 1993) for events shallower than 15 km in all regions

- A_{max} has been assumed to be 2500 gal for all points of computation

- each solution at each field point was iterated 100 times with pseudo-random numbers

The CLIM94 attenuation relation is the best documented of all those suggested and appears to have a good balance of near and far field data available for the computation of its coefficents. Its peak values are somewhat lower than those computed using other attenuation relations, but this will have to be accepted until improvements in our knowledge and understanding of attenuation can be made.

As there is no analytical method available at this time for establishing the value of A_{max}, several values were tried and checked for such things as A_{max} being exceeded (forcing an arbitrary but unacceptable reset within the computer programme to a value 1 gal less than A_{max}). The results of these tests suggest that no great error is introduced into the calculations by using a single value for all field or target points which then led to the adoption of the value 2500 gal for A_{max}; a value that is nowhere exceeded by the result of any single interation.

Pseudo-random numbers provide an excellent low pass filter and when combined with the smoothing in both the gridding and contouring processes of SURFER, the result is a sesimic hazard map devoid of a a large number of "bullseyes" which we believe to be an undesirable feature.

Our technique of extrapolation to the desired return period, the use of the CLIM94 relation and the smoothing inherent in the use of pseudo-random numbers lead to peak seismic hazard values that are slightly lower in the high range of hazard values than those on maps for South America and México compiled by CERESIS and UNAM respectiveley. However, a comparison of the mean values of each of the "five levels" (see above) of seismic hazard computed for the IPGH maps with those computed by the regions gives good agreement generally for the four lower levels and fair agreement for the upper level. For the moment this is about the best we can expect, but there is no doubt that the IPGH maps a reasonable reference map for the project area as a whole.

As our catalogue covers a time interval of about 500 yr and several participants have expressed interest in seeing a map of maximum PGA due to a single event, we have computed and compiled a map of what we call "one-time maximum" hazard values using the CLIM94 attenuation relation. Comparison with the probabilistic map suggests that the values are for the most part everywhere less. However, we emphasize that this "one-time maximum" map has no meaning in a probabilistic sense and cannot be used in place of it.

Resumen

El Comité Directivo del Proyecto de Peligro Sísmico - América Latina y el Caribe - le indicó al IPGH la compilación de un mapa probabilístico de peligro sísmico en "cinco niveles" para el área de proyecto usando el método paramétrico histórico para calcular las estimaciones en la rejilla. Este mapa servirá de referencia común para los mapas de peligro sísmico que serán producidos en forma independiente por cada una de las regiones usando el procedimiento de cálculo de su elección (exceptuando el Caribe, todos los demás escogieron el método de zona fuente).

Los cinco niveles de peligro sísmico definidos por el Comité Directivo son:

0 - 62.5 gal - peligro menor
62.5 - 125 gal - peligro bajo
125 - 250 gal - peligro moderado
250 - 500 gal - peligro significativo
> 500 gal - peligro elevado

El programa de computadora desarrollado por el IPGH especialmente para el proyecto y esta asignación tiene las siguientes caracteristicas:

- incorpora en el cálculo las incertidumbres estimadas de los parámetros de los sismos utilizando números pseudo-aleatorios para escalar las desviaciones estándar asignadas a cada parámetro, se asumió que todos los parámetros tienen una distribución normal, exceptuando aquellos (profundidad y atenuación) que pueden generar valores menores a cero, en cuyo caso asumimos una distribución log-normal.

- se removieron las secuencias de réplicas de la lista de sismos usadas para el cálculo, usando el método de Davis y Frolich (1991), con un intervalo de corte de setenta y cinco (75) días "espacio-tiempo".

- se efectuó una extrapolación al periodo de retorno requerido (474.56 años para un 10% de probabilidad de excedencia en 50 años), utilizando la siguiente ecuación:

$$\ln A = \ln A_{máx} - ae^{-\beta R}$$

donde α y β son constantes que deben ser estimadas de los datos, $A_{máx}$ es el valor máximo posible de PGA en el campo o punto de interés y R es el periodo de retorno. Cuando $R \rightarrow \infty$, $A \rightarrow A_{máx}$.

De nuevo, con la aprobación de Comité Directivo, el programa de computadora se aplicó bajo las siguiente condiciones:

- todos los eventos con magnitud de momento $M \geq 4$ fueron seleccionados del catálogo de sismos,
- se considera que el catálogo está completo para $M \geq 4$ durante el periodo 1964 - 1993,
- seleccionamos la relación de atenuación CLIM94 para los cálculos, de entre las siguientes relaciones de atenuación proporcionadas por el Comité Directivo
  - ORDAZ94 (Mario Ordaz de la UNAM, comunicación personal, 1994),
  - CLIM94 (Climent et al, 1994),
  - KAUSEL94 (Edgar Kausel, Universidad de Chile, comunicación personal, 1994),
  - WC82 (Woodward-Clyde, 1982)
- el Comité Directivo también requirió el uso de JB93 (Boore et al, 1993) para eventos mas superficiales que 15 km, en todas las regiones
- para $A_{máx}$ se asumió un valor de 2500 gal en todos los puntos de cálculo
- cada solución para cada uno de los puntos de campo fue iterada 100 veces usando números pseudo-aleatorios.

La relación de atenuación CLIM94 es la mejor documentada de todas las que fureron sugeridas y parece tener un buen equilibrio entre los datos de campo cercanos y lejanos disponible para el cálculo de sus coeficientes. Sus valores máximos son algo menores que los calculados usando otras relaciones de atenuación, pero esto debe ser aceptado hasta que haya mejorado nuestro conocimiento y comprensión de la atenuación.

En vista de que hasta este momento no existe ningún método analítico disponible para establecer el valor de $A_{máx}$, se probaron y se revisaron diversos valores para situaciones tales como que $A_{máx}$ sea excedido (lo que obliga a que el programa de computadora lo redefina en forma arbitraria e inaceptable a un valor de 1 gal menor de $A_{máx}$). Los resultados de estas pruebas sugieren que no se introducen grandes errores en los cálculos por el hecho de usar un valor único para todos los puntas seleccionados o de campo, lo que condujo a adoptar el valor 2500 gal para $A_{\text{máx}}$; valor que no es excedido en ninguna parte por el resultado de cualquiera de las iteraciones individuales.

Los números pseudo-aleatorios proporcionan un excelente filtro pasa-bajas y al combinarlos con el suavizamiento tanto en la rejilla como en los procesos de contorno del SURFER, el resultado es un mapa de peligro sísmico sin la presencia de un gran número de "ojos-de-buey" los que consideramos una característica indeseable en estos mapas.

Nuestra técnica de extrapolación al periodo de retorno deseado, el uso de la relación CLIM94 y el suavizamiento inherente al uso de números pseudo-aleatorios, producen valores pico de peligro sísmico que son menores que los proporcionados para el rango de peligro elevado en los mapas para América del Sur y México compilados por CERESIS y UNAM respectivamente. Sin embargo, comparando los valores medios entre los mapas de peligro sísmico calculados para el IPGH con aquéllos calculados por cada región, para cada uno de los "cinco niveles" de peligro sísmico (ver arriba), encontramos que, para los cuatro niveles inferiores existe una buena concordancia general, mientras que para el nivel superior la concordancia es razonable. Por el momento, esto es lo mejor que podemos esperar, pero no hay duda de que los mapas del IPGH son mapas de referencia razonables para el área total del proyecto.

Como nuestro catálogo cubre un periodo de tiempo de 500 años y varios participantes han expresado su interés en ver un mapa de PGA máximo debido a un evento aislado, calculamos y compilamos un mapa de valores de peligro sísmico de lo que llamamos "máximo - por - única - vez", usando la relación de atenuación CLIM94. La comparación con el mapa probabilístico de este mapa muestra que en le mayor parte, los valores producidos son menores. Sin embargo, deseamos enfatizar que este mapa "máximo - por - única - vez" no tiene sentido desde un punto de vista probabilístico y no puede ser usado en su lugar.

Part 1. Methodology

Introduction

The classic paper by Cornell (1968) represents the beginning of what might be called the modern era of seismic hazard estimation. In this paper Cornell laid the foundation for probabilistic seismic hazard estimation by means of the source zone method. Subsequently, many individuals, notably in the USA, have contributed enhancements to this method to the point where a rather sophisticated industry exists. Despite these advances in the art we should never forget that good results depend to the first order on the catalogue upon which the computations are based. In the absence of a top quality catalogue with magnitude estimates on a uniform scale (preferably moment magnitude), seismic hazard estimates to modern standards are not possible.

For this project the Steering Committee took the position that each region should compute its own seismic hazard estimates by a method of its choosing and that the project (IPGH) would compute, or otherwise compile, a map of global estimates of seismic hazard to provide a reference for comparing seismic hazard estimates from locale to locale within the project area. This decision was further refined at the meeting in Brazil where the committee decided that, the project office would compile a "five-level-seismic hazard map" because several members believed there might be serious problems in the event a contoured project map differed from that extant in any particular country. The values of PGA upon which these five subdivisions would be based were also established and IPGH was asked to compile such a map for discussion at the next meeting of the Steering Committee.

As considerable research and development had already been done on a method of seismic hazard estimation that was fast on a computer and easily adapted to situations where extensive testing and evaluation were required, IPGH decided to apply this method to the assignment from the Steering Committee. Known as the *Historic Parametric Method*, our development of it proved equal to this task and one of us (JBS) presented a five level seismic hazard map to the next meeting of the Steering Committee in Melbourne, Florida. The Steering Committee directed that IPGH compile such a map for the final report of the project based on a 10% probability of exceedance in 50 years.

The project office developed an operational version of the computer programme which included adaptations related to the use of random numbers, to the method of extrapolation to the required return period (in our case 474.56 yr) and to the removal of aftershock sequences. The final hazard map was compiled and presented for the approval of the Steering Committee at its final meeting (in Melbourne, Florida in 1995).

We proceed first to a brief description of our version of the historic parametric method, followed by a presentation and discussion of the seismic hazard maps. Our conclusions follow.

The historic parametric method

Diverse and often equivocal discussions between the authors regarding the computation of seismic hazard estimates eventually led to the programming and testing of an early version of our adaptation of this method by JBS and his graduate students at Lancaster University in the UK. This method at the time was believed to be original, but subsequently we found that others (e.g., Grases, 1990; Veneziano, Cornell and O'Hara, 1984) had considered the method before us. Nevertheless, we persisted with the development of this method because it was fast on a computer and therefore offered the opportunity of testing a wide variety of hypotheses for the hazard calculations before the final computations were necessary.

Some of the main points that emerged from our early discussions are:

- Most of the existing computer programmes were cumbersome and time consuming and not at all suited to testing various hypotheses quickly on a PC.
- The choice of source zones was (and is) subjective with the result that different individuals and groups would almost certainly derive different models.

- Patterns of seismicity often influence to a considerable extent the choice of source zones.

- The only real evidence for a particular fault being active is an earthquake and in this sense it might be better to allow the earthquakes individually to define hazard rather than assume that any given event may occur anywhere within a given source zone.

- Inclusion in the seismic hazard computations of uncertainties in the data contained in the catalogue is relatively easy to carry out with the Historic Parametric Method.

- Extrapolation in one manner or another is a necessary evil in any technique of computing seismic hazard.

Comparisons of the results using this method with the source zone method by students at the University of Lancaster in the UK and presented at various technical workshops of the project showed clearly the methods gave comparable results. This, among others, led to the decision of the Steering Committee to retain the method for use in the compilation of the five level reference map by IPGH.

Shepherd, Tanner and Prockter (1994) presented the results using an early version of our computer programme. Since that time we have added the use of pseudo-random numbers, an improved, we think, method of extrapolation and removal of aftershock sequences. More will be said of these later.

We start with the usual assumptions that the distribution of earthquakes with time is Poissonian and that rate of activity of any given source follows the Gutenberg-Richter relationship:

$$Log N = a - bM. \qquad (10)$$

We then proceed as follows:

1. Define the periods of completeness for different magnitude ranges (for a catalogue covering a period 1471 to mid-1994 we have chosen a completeness interval of 30 yr (1964-1993) for all events with magnitude $M \geq 4.0$).

2. Choose the attenuation relation(s) to be used for the region under consideration (in our case we are interested in the computing the ground motion at sites on solid rock or equivalent).

3. Select the earthquakes to be included in the computation (in our case those events of magnitude 4 or 4.5 and above, all depths and no area restrictions (i.e., select from the entire project area)) for the region under consideration.

4. For each earthquake selected, calculate the distance of its hypocentre from and then the Peak Ground Acceleration (gal) at the field or target point under consideration using pseudo-random numbers generated by standard methods (Press, Teukolsky, Vettering and Flannery, 1992) to scale estimated uncertainties of the parameters involved in the computation..

5. Set up a series of bins, each with an increasing threshold of acceleration, and compare the computed level of acceleration with each until a bin is encountered with a threshold that is larger than the computed acceleration - for each bin accepted augment the number of events by one.

6. Once all earthquakes selected have been processed, compute the return period for the events in each bin, rejecting any bin with less than three events - the longest possible return period is thus 10 yr in our case.

7. Extrapolate the bin information (acceleration level and return period) to the required return period (we have used 456.74 and 10000 yr) - use at most the five adjacent bins with the largest return periods and abandon the computation point should any iteration contain less than three bins meeting the specifications for extrapolation.

8. Iterate steps 4-7 100 times (or more if time of computation is not an important factor) placing the results in an array of estimated PGA values - in our programme we do not use random numbers for the first iteration so that we can compare randomized and non-randomized results.

9. Calculate the median and upper and lower quartiles for the randomized acceleration values for each target point.

10. Step to the next point in the area under consideration and repeat steps 4-9.

We now turn to a consideration in more detail of some aspects involved in the computation of seismic hazard.

Attenuation relations

Seismic waves are affected by physical conditions near the focus of the event, by physical conditions between the focus and the target point and by local conditions beneath the target point. Conditions of this complexity underscore the difficulties of deriving an expression for the attenuation of seismic waves in the estimation of probabilistic seismic hazard, especially for an area of the size involved here. They also help understand why attenuation of seismic waves is one of the largest sources of error (up to a factor of two for this area) in the calculation of probabilistic seismic hazard estimates..

The project grappled with the problem of attenuation at various meetings of the Steering Committee and Technical Workshops without reaching a conclusion. At a meeting of the Steering Committee in Melbourne in May, 1994, we were fortunate to have in attendance Dr. Mario Ordaz of UNAM who is among the most knowledgeable of individuals in Latin America on this subject. At this meeting each regional representative suggested what he thought to be the attenuation relation best suited to computations of seismic hazard for their respective regions. Each was carefully reviewed with Dr. Ordaz by programming it on a notebook computer to study its behaviour with distance and to compare it with the others.

To avoid problems of too rapid attenuation in the vicinity of the epicentre, the Steering Committee decided, on the recommendation of Dr. Ordaz, to apply the Singh et al (1980) equation, an empirical relationship which relates the magnitude of an event to the area of the fault zone (here termed the "Singh rupture sone"). In the form used by Singh et al this equation is written

$$M = a \log A + b$$

where a and b are constants here assigned the values 1 and 4 respectively, A is the area of the fault zone and M is the magnitude of the event. If we assume that the rupture area is square, this equation can be inverted to define a half-width (RD) of the fault zone as follows:

$$RD = 1/2(10^{M-4})^{\frac{1}{2}} \qquad (11)$$

where RD is the distance from the epicentre to the edge of the "Singh rupture zone" and M is the moment magnitude of the event. For our purposes Dr. Ordaz recommended that RD be limited to a maximum distance of 37 km.

The four attenuation relations proposed for the consideration of IPGH are:

1. México

Provided by Ordaz (1994, personal communication) this law is:

$$A = 1.76 + 0.3M - \log D - 0.0031D \qquad (12)$$

Where A is the acceleration in gal, M is the moment magnitude and D is the depth to the focus if D is less than RD (equation 11) or else the distance from the target point to a focus transposed to the edge of the "Singh rupture zone". Dr. Ordaz also recommended that the maximum acceleration values generated by this equation be limited as follows:

- If $M \geq 8$ then $A_{max} = 526$ gal;

otherwise

- $A_{\max} = 253 - 162M + 265m^2$ gal.

Central America

The coefficients of this attenuation relation have been computed from the results of about 220 strong motion recordings (Climent et al, 1994), of which about 60 are located in México and about 90 on hard rock locations. The coefficients have been computed for eight different frequencies, although we do not use it in this mode. The relationship as used in this report is:

$$\ln A = -1.687 + 0.553M - 0.537\ln R - 0.00302I \qquad (13)$$

where M is the magnitude and R is the depth to the focus if R is less than RD of equation 11 or the distance to a focus transposed to the edge of the "Singh rupture zone".

South America

This relation has been derived by Edgar Kausel (personal communication) of the Universidad de Chile and recommended to the Steering Committee by Alberto Giesecke, the Director of CERESIS. No details are available as to the numbers and distribution of strong motion recordings nor the method of determining its coefficients. The equation as used in this report is:

$$\ln A = \ln 71.3 + 0.83M - 1.03\ln(R + 60 \qquad (14)$$

where M is the magnitude and R the distance computed in the context of the "Singh rupture zone". Dr. Kausel has also recommended additional constraints on the maximum acceleration values generated by this equation as follows:

- for $M \geq 9$ the maximum acceleration permitted is 525 gal
- for $M \geq 8.5$ the maximum acceleration permitted is 520 gal
- for $M \geq 8$ the maximum acceleration permitted is 512.5 gal
- for $M \geq 7.5$ the maximum acceleration permitted is 500 gal.

Constraints on the accelerations of very large earthquakes have been applied in both México and South America on the basis of strong motion recordings which show that these large events do not produce the peak accelerations that have been observed elsewhere for events of similar magnitude.

The Caribbean

Aspinall et al (1994) examined a number of attenuation relationships and concluded that the equation developed by Woodward-Clyde (1982) for subduction zone settings best fit the scene in the Trinidad-Tobago region. Although this is intended for subduction zones this has been suggested for consideration by the project office for all of the Caribbean, largely because it agrees as well or better than other relations with the limited data available.. This relation is:

$$\ln A = 5.347 + 0.5M - 0.85\ln(D + \exp(0.463M) \qquad (15)$$

where D is the distance within the contexr of the "Singh rupture zone" and M is the magnitude.

Shallow events

As indicated earlier the meeting of the Steering Committee undertook an extensive discussion of the effects of shallow earthquakes (say at depths of less than 15 km) and concluded, albeit reluctantly on the part of one or two individuals, that some allowance should be made in the compilation of the maps at the project level for the increased accelerations observed in the event of shallow earthquakes. Consequently, we decided to include the Joyner and Boore (1993) relationship in the computations and to apply it to those events with depths of 15 km or less.

This law as used here is:

$$\log A = -1.229 + 0.227M - \log(D^2 + 44.225)^{\frac{1}{2}} - 0.00231(D^2 + 44.225)^{\frac{1}{2}} \qquad (16)$$

where D is the distance within the context of the "Singh rupture zone" and M is the magnitude.

The Steering Committee concluded its lengthy discussion on attenuation with the recommendation that IPGH choose any or all of these relations to compute its reference map for the project area.

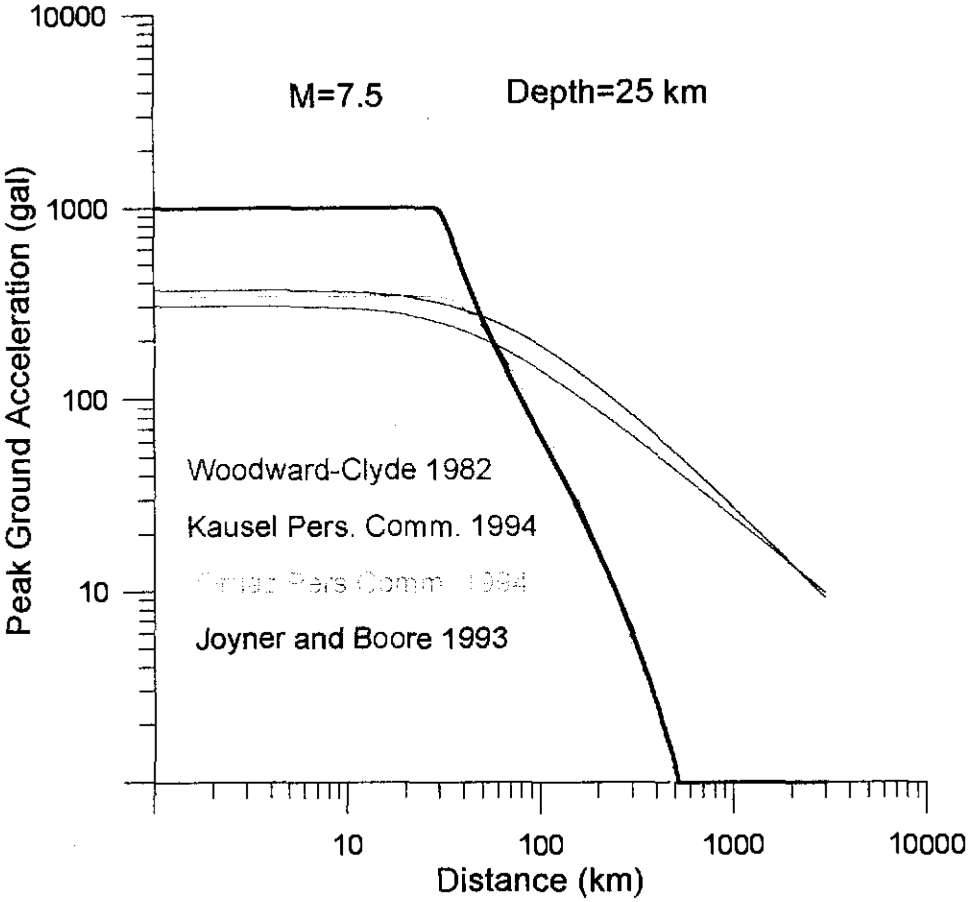

Figure 10. Behaviour with distance of the five attenuation relations considered in this report. Note that these relations are assumed to hold over the range for which they are non-zero, which may differ from the limitations imposed by the originators of the particular relation

A comparison of the four attenuation relations (the Joyner and Boore relation is included for completeness, but is intended only for use with shallow earthquakes) is given in Fig, 10 from which we draw the following conclusions:

- The Kausel and Woodward-Clyde relations attenuate very slowly and would produce probabilistic seismic hazard maps for which the pattern of the contours would be far broader than any we have seen to date. This behaviour probably stems from limited horizontal distances over which strong motion data are available or their distribution or a combination of both, with the result that the relation can only be applied over a restricted horizontal distance. Dr. Kausel (personal communication) has confirmed this in the case of the attenuation law he used in Chile. We therefore conclude we can not use these relations in the general case.

- The CLIM94 law attenuates more slowly than does ORD94, but its peak value is lower for an earthquake of the magnitude used to compile Fig. 10. As the CLIM94 law includes data for México, it would appear to have the good balance of near and far field strong motion records necessary for an attenuation law to be representative of the conditions found within the project area. The rapid attenuation of ORD94 seems to be too severe for general use.

Discussions with various individuals involved in the project indicated general agreement to use the CLIM94 to compute probabilistic seismic hazard estimates for the project map.

There is always a concern about the distance over which the particular attenuation law is valid. Boore et al (1993) for example tend to limit this distance in the interests of avoiding correlations that might otherwise bias the results. Others (Climent et al, 1994) use all of the data available. We also note that the events for which strong motion recordings exist are most likely greater than magnitude 6 or 6.5 which introduces another bias since we use these relations for all magnitudes. Problems of distance and magnitude range accepted, we have applied these relations universally assuming in the process solid rock or equivalent as the medium of response. This rather generous extrapolation on our part does not seem to have produced erratic results if comparisons with the results of other methods are any measure.

Finally, we note that operating agencies in each of the regions are in the process of modernizing their equipment and we hope that in the not-too-distant future a comprehensive review can be made of the different attenuation relations determined from data collected in the regions.

Selection of earthquakes

For events smaller than 4.5 the moment magnitude scale is probably not uniform. The contribution of events of magnitude 4 to the final hazard estimates is very small, but the presence of acceleration values due to these events may be useful in providing the minimum of three levels required for the extrapolation process. In some cases, however, the smallest levels of acceleration may not be considered because of the way in which exptrapolation is applied (see above).

We experimented with areas of various sizes and found that the penalties in terms of computation time were not that great if we chose all the events in the project area meeting the magnitude and depth criteria. Undoubtedly we are extending the attenuation relations well beyond their range of actual observation. As we are calculating the effects on solid rock or equivalent, we must assume a more uniform and predictable response of the medium at greater distances with the result that any errors due to this extrapolation are not large.

Each earthquake is considered as an isolated or point source and not part of some larger source zone of whatever definition. Earthquakes that have occurred within the period of completeness define the patterns to be used for the seismic hazard estimates. Although this approach has its problems when the rate of seismicity for a given area is very low (a problem for any method), the results generally compare well with those of other methods.

The use of pseudo-random numbers

One of the features of our seismic hazard estimation computer programme is the inclusion of procedures in the computation of the seismic hazard estimates that use pseudo-random numbers to scale uncertainties assigned to the earthquake parameters used in the calculation. Iterative procedures then lead to a solution based on some optimum arrangement of the number of iterations needed to give a reasonable statisical sample and the time to compute the particular result.

For each earthquake the predicted PGA at the target site depends on the location of the earthquake relative to the target site, its magnitude and the ground motion relationship. For our computations we have made the following assumptions with respect to these parameters:

- Uncertainties in the latitude and longitude of the earthquake are normally distributed with a mean of zero and a standard deviation of 0.25 deg.

- Uncertainty in the magnitude of each earthquake is normally distributed with a mean of zero and a standard deviation of 0.25 units of magnitude.

- Uncertainty in the focal depth is log-normally distributed, i.e.,

  $$\ln Z = \ln Z_0 + \delta_z$$

  where Z_0 is the nominal depth and $\delta_z = 0.1 Z_0$ is a normally distributed quantity with a mean of zero.

- Uncertainty in ground motion is also log-normally distributed, i.e.,

  $$\ln A = \ln A_0 + \delta_A$$

  where δ_A is normally distributed with a mean of zero and a standard deviation as stated by the authors of the ground motion equation.

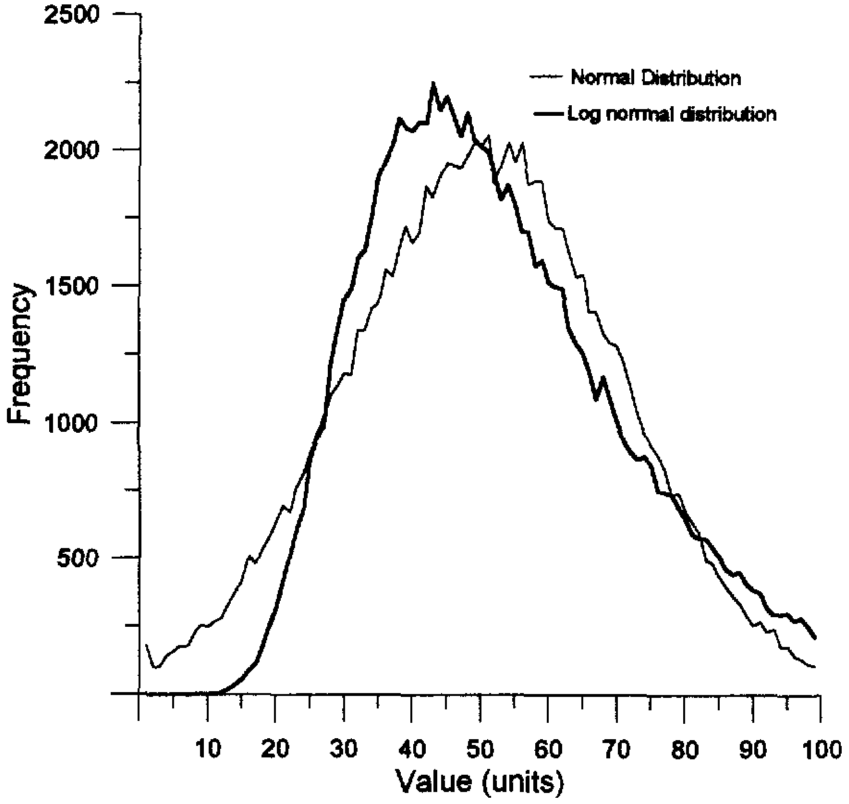

Figure 11. Comparison of the normal and log-normal distributions for a parameter with the same uncertainty. The ragged appearance of the two graphs is a consequence of the limited number of iterations and the number of divisions used to compile the histogram. Considerable smoothing could be achieved by expanding the cell width to 2 or 3 units.

Fig. 11 shows a comparison of the normal and log-normal distributions for a parameter with a value of fifty (50) with error estimates of ±20 units and ±0.4 X respectively, where X is any variable. The skewed distribution of the log-normal distribution is readily apparent. This skewness does not affect the median computed for each curve (both have a median of 50), but the upper and lower quartiles differ for each curve, as might be expected. Note also that the normal distribution results in negative values for the variate, which would force some arbitrary choice such as setting the variable to zero which would bias the computed result.

For our computations we have specified that 100 iterations are sufficient to determine the computed result as this was found to be an optimum combination of time saving and accuracy . Fig. 12 gives a probability density function (PDF) for both 100 and 1000 iterations for a station located in the Caribbean. The PDF for 100 iterations is more ragged than that for 1000 iterations, but gives about the same result as expressed in terms of the median. However, the time required to compute the result is about ten times greater in the case of 1000 iterations. Even with the fastest (at the time) of PCs available to the project the time needed to complete the calculations using 1000 iterations per point of computations would be months and not days as was the case for

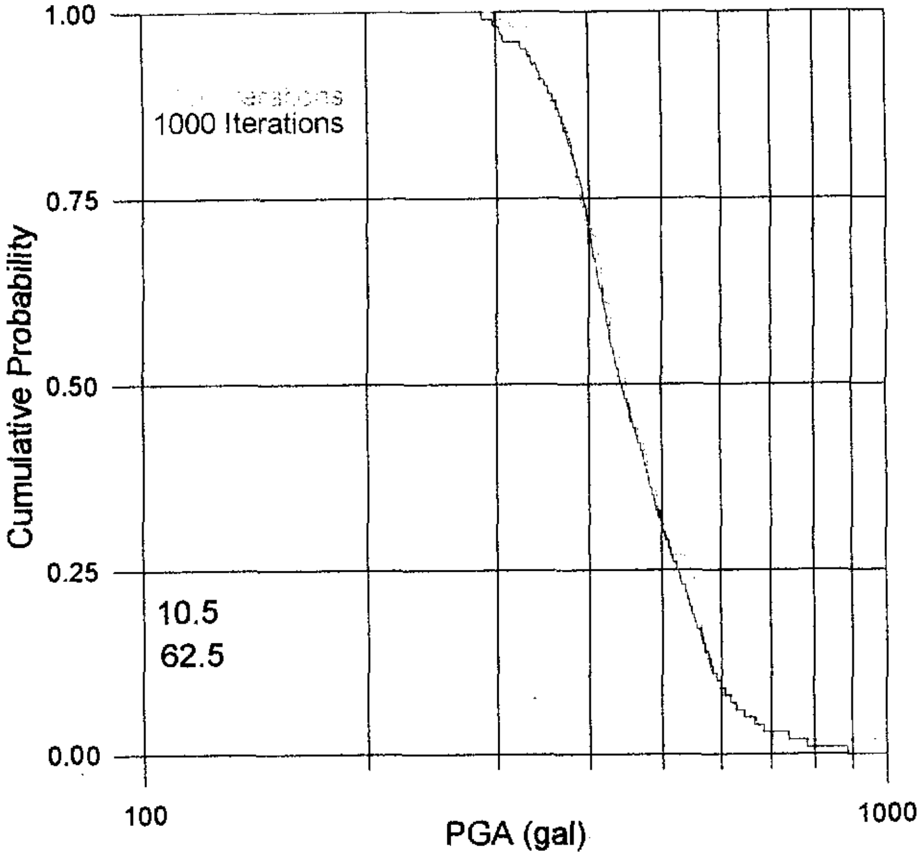

Figure 12. Probability Density Function (PDF) for solutions determined from 100 and 1000 iterations using the random number generator. Aside from a more ragged PDF for 100 iterations the two solutions give about the same result.

100 iterations in an area the size of South America. This time is unacceptably long and we therefore opted to use 100 iterations for each point of computation in all regions.

We have used the more portable and, we think, better random number generators available in Press, Teukolsky, Vettering and Flannery (1992). We have employed a combination of their functions GASDEV and RAN1. RAN1 produces a string of random numbers with values uniformly distributed between 0 and 1 and GASDEV converts these to a normal distribution with a mean of zero (0) and a standard deviation of one (1). We tested all the other random number generators given by Press et al with about the same results.

Extrapolation

To determine the seismic hazard estimate on the basis of a 10% probability of exceedance in 50 yr we must extrapolate to a 474.56 yr return period from a maximum possible calculated return period of 10 yr (for a catalogue with a period of completeness for $M \geq 4$ of 30 yr and a requirement that there must be at least three events in any given bin to calculate a return period for that particular level of acceleration). The return period for any given probability can be calculated from the expression $P(a) = -e^{\frac{t}{R}}$, where P(a) is the probabilitiy, t is the lifetime of the particular edifice (in this case 50 yr) and R is the return period for which the probability is valid. If we substitute the value 0.90 (90% probability of non-exceedance) and the value 50 for t into this equation we get the value 474.56 for R. Interested readers should look up Algermissen et al, 1982 for a good discussion of this topic.

We now set about a brief development of the method of extrapolation used for our calculations. We start with the following assumptions:

- The ground motion law is of the general form

$$\ln A = c_1 + c_2 M + c_3 \ln(R + c_4) \qquad (17)$$

- Source zones are infinitesimal elements of volume

- Within the i'th source zone the rate of earthquake occurrence is governed by the Gutenberg-Richter law

$$\ln N_i = a_i - b_i M$$

- a_i varies from element to element and b_i is assumed constant for all elements (Scholz (1990) for example has argued that when M is the moment magnitude scale this quantity should be constant).

Let **A** be the ground motion generated at site **j** by an earthquake of magnitude M in element **i**. Then from equation 17

$$M = \tfrac{1}{c_2}(\ln A - (c_1 + c_3 \ln(R + c_4)))$$

where R is the return period. The quantity ($c_1 + c_3\ln(R + c_4)$) depends only on the combination of site and element and on the ground motion relationship. We can therefore replace it with a constant a_{ij}. Therefore

$$\mathrm{M} = \tfrac{1}{c_2}(\ln A - a_{ij})$$

Combining this equation with the Gutenberg-Richter relationship (see above), we have

$$\ln \mathrm{N_i} = a_i - \tfrac{b_i}{c_2}(\ln A - a_{ij})$$

$$= \{a_i + \tfrac{b_i}{c_2} a_{ij}\} - \{\tfrac{b_i}{c_2} \ln A\}$$

N_i is the total number of earthquakes in the i'th source zone which generate a ground motion of A or greater. We also note that

- the term inside the first set of curly brackets depends on the activity rate in the i'th source zone and on the constants defining the ground motion relationship. It therefore depends on both i and j.

- subject to our assumption that b is constant over all source zones, the term $\frac{b_i}{c_2}$ is a constant over all source zones.

The total number of occurrences of ground motion of amplitude A or greater at the j'th site is

$$(N_A)_j = \sum_{i=1}^{n} N_i$$

where n is the total number of elemental sources. Therefore

$$(N_A)_j = \exp[(\frac{-b}{c_2}\ln A)\sum_{i=1}^{n}(a_i + \frac{b_i}{c_2}a_{ij})]$$

which can be written

$$\ln\{(N_A)\} = \{\sum_{i=1}^{n}(a_i + \frac{b_i}{c_2}a_{ij})\} - \frac{b}{c_2}\ln A$$

or for simplicity

$$\ln\{(N_A)_j\} = \mu_j - \frac{b}{c_2}\ln A$$

The reciprocal of the number of events per unit time is the return period, R, so that we have finally

$$\ln R = \ln(\frac{1}{(N_A)_j}) = \frac{b}{c_2}\ln A - \mu_j$$

or

$$\ln A = \frac{c_2}{b}\ln R + \frac{c_2}{b}\mu_j$$

as the equation relating the level of ground motion to the corresponding return period. An alternative form of the relationship is the power-law representation suggested by Grases (1990)

$$A = aR^{\beta} \tag{18}$$

The unmodified power-law relationship is unbounded at the upper end. That is, it predicts that as

$$A \to \propto R \to \infty.$$

We consider that this result is physically unreasonable - it follows from the fact that the simple Gutenberg-Richter relationship allows all magnitudes up to M = ∞. In order to remove this feature we have used an extrapolation relationship of the form

$$\ln A = \ln(A_{\max}) - \alpha \exp(-\beta R \qquad (19)$$

where α and β are new empirical constants determined from the data and $A_{\max}$ is the maximum possible PGA at the site. This relationship is exactly equivalent to the power-law relationship when A is small compared with $A_{\max}$, but has the property

$A \rightarrow A_{\max}$ as $R \rightarrow \infty$.

Fig 13 illustrates the extrapolation procedure used in this study for a field or target point in an area in which the rate of seismicity is low (eastern central Brasil). The plus marks in this diagram represent the return periods and acceleration levels upon which the extrapolation has been based - the programme considers only the top five points if more than five exist. (Recall that a minimum of three valid bins, each of which contains the results of processing three events or more that meet or exceed the acceleration level for the particular bin, are required for the point of calculation to

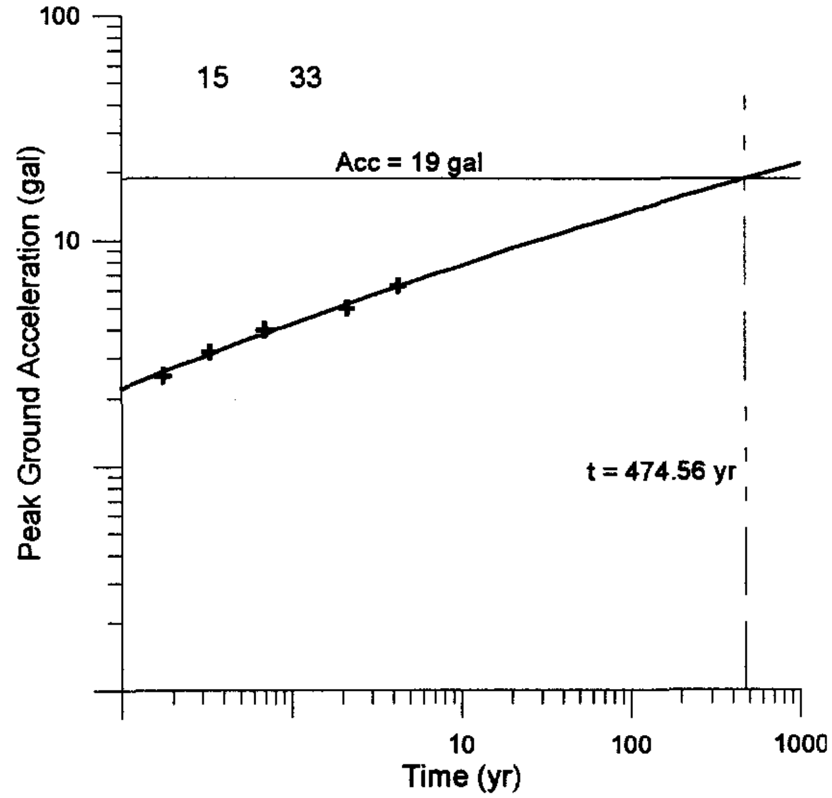

Figure 13. Extrapolation of PGA versus return period by means of the method outlined in the text for $A_{\max} = 2500$ gal. This target point is located in an area of low seismicity in east central Brasil.

be accepted). All points that we have checked, admittedly limited, in the above manner have five values available for the extrapolation to 474.56 yr.

We have been unable in the time available to arrive at some quantitative method of determining A_{max}. There is also the problem with random numbers of any iteration producing a value in excess of A_{max}, forcing some arbitrary decision to reduce it to less than A_{max}. Any such arbitrary action is unacceptable. Experimentation has shown the results do not differ in a major way due to choice of A_{max} with the consequence that we have tended to adopt the rather large value of 2500 gal. This value has been approached at some target points within the project area, but to our knowledge has not been exceeded.

Fig. 14 shows the results for three different values of A_{max} for one of our favourite test points in the Caribbean. As can be seen from the diagram there is relatively little to choose between the three values. In this case A_{max}= 2500 gal produces a somewhat larger result than the others with A_{max} = 2000 gal producing the smallest value; the differences are probably a result of the use of random numbers. We checked a sample of 10 values calculated with A_{max} = 2500 gal and found a

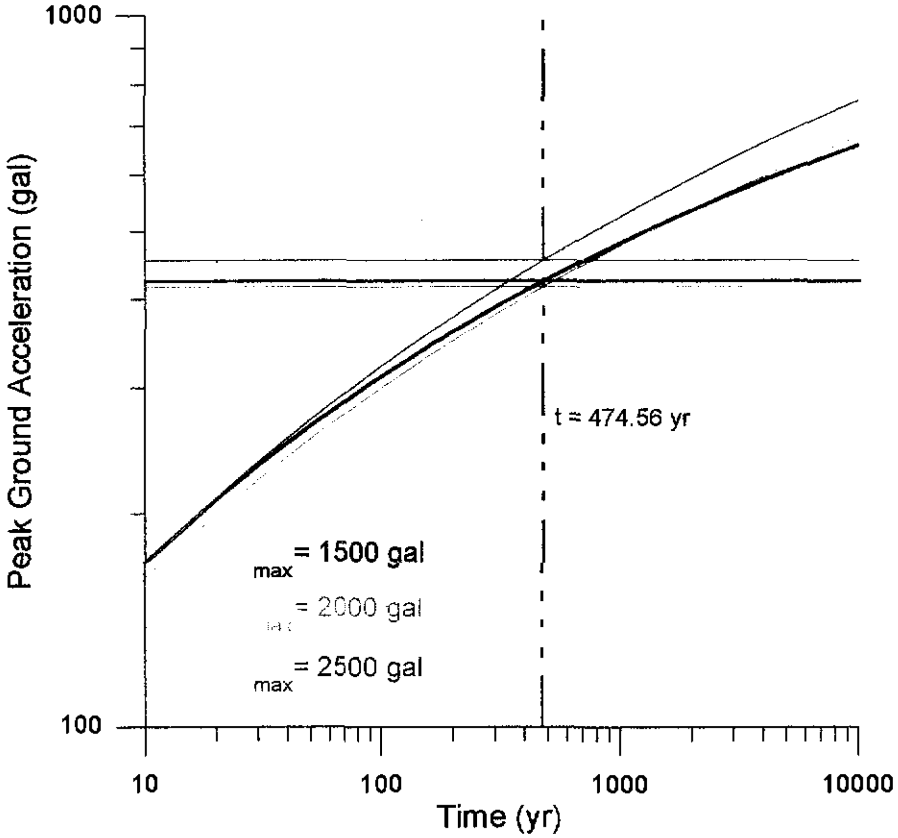

Figure 14. Comparison of extrapolations using three different A_{max} values for a computation point located in the Caribbean. The estimated hazard values vary from 424 gal for A_{max} = 1500 gal (black) to 454 gal for A_{max} = 2500 gal (green) with A_{max} = 2000 gal (red) producing the smallest value. The differences are probably due to the use of pseudo-random numbers..

mean of about 450 gal with the spread between the maximum and minimum values being 40 gal or just less than 10%. Perhaps more indicative of the behaviour of the results with different values of A_{max} are those obtained without the use of random numbers. These can be seen in Table 4 which shows the computed PGAs with and without the use of random numbers for three different A_{max} values. This table shows that the computed PGA without the use of random numbers decreases by about 6% as A_{max} decreases from 2500 to 1500 gal which suggests that in this case 1500 gal might have been a better choice for A_{max} as the computer gave no indication that A_{max} had been exceeded.

Unfortunately we have not been able in the time available to establish an optimum value for A_{max} on a target point by point basis. Giving the computer special instructions on how to assign the A_{max} value for each field point would be a monumental and time consuming (never ending might be more appropriate) task. Our conclusion is that the use of $A_{max} = 2500$ gal does not seem to produce results that are too much different from those for lower values and as we know it is not exceeded anywhere in the project area during any iteration using random numbers, its use seems to be as reasonable as any other value of A_{max}.

Table 4
Variation of PGA with A_{max}

A_{max}	Random Numbers	Normal
2500	454	335
2000	416	327
1500	424	316

Table 4 also shows that the seismic hazard values computed using random numbers are larger than those computed without random numbers - comparisons in the Caribbean show an average increase of about 30% in the computed seismic hazard with the use of random numbers. This increase probably occurs because the behaviour of PGA is logarithmic and therefore the contribution of an augmented parameter is greater than that for a diminished parameter. The use of random numbers also smoothes the computed seismic hazard values, and we would expect that any contoured seismic hazard map compiled with their use would contain fewer isolated high and low values than that compiled from unmodified parameters.

Aftershock sequences

To remove aftershocks from the computations of seismic hazard, we have adopted the method suggested by Davis and Frolich (1991) who describe a procedure using what they call single-link cluster analysis. They have suggested the empirical relationship

$$d_{ST} = \text{space-time "distance"} = (d^2 + C^2 T^2)^{\frac{1}{2}}$$

where d is the geographic separation, in three dimensional Euclidean space, between earthquakes, T is the time difference (days) and C is a parameter that relates time to distance. They also suggest the value one (1) for C which is a sort of tectonic constant for any given area. In their Table 1, their results suggest a cut-off distance (i.e., a maximum value for d_{ST}) for any possible linkage of 70 to 80 ST-km for our project area - we have taken the mid-point of this range of values and have used 75 ST-km as the limit for tagging aftershocks.

When this aftershock sequence relationship is applied to our catalogue we get the following results when selecting the earthquakes for the computations:

- for $M \geq 4$ there are 31,447 events of which 10,947 are tagged as aftershocks,
- for $M \geq 4.5$ there are 11,737 events of which 2,672 are tagged as aftershocks.

Part 2: Seismic hazard maps

Introduction

The seismic mapping hazard procedure as employed here is summarized as follows:

- Select the target site(s)
- Select the earthquakes meeting the retrieval criteria and tag those that are determined to be aftershocks
- For every earthquake selected, calculate the PGA at the target site.
- Repeat the calculation 100 times perturbing the earthquake parameters during each iteration by pseudo-random numbers which scale the estimated standard deviation of each earthquake parameter.
- Find the median and upper and lower quartiles of the resulting distribution.
- Place the acceleration for this site in the file to be used for extrapolating to the required return period.
- Repeat for all earthquakes.
- Extrapolate to $R = 474.56$ yr.
- Step to the next site and continue until all sites are completed.
- Grid, contour and plot the data.

All maps presented in this section have been compiled from the data computed with our seismic hazard programmes with the latest WINDOWS version of SURFER (trademark registered to Golden Software in Colorado, USA), an easy-to-use system that can produce outputs that are professional in their appearance. Like all such contouring systems, SURFER can get into difficulty due to aliasing in regions of high horizontal gradient. We have attempted to overcome this by using this system's matrix smoothing method which acts as a low-pass filter. This approach removes genuine as well as spurious highs and lows.

Results

Maps produced entirely by IPGH for presentation in this report have been compiled from results obtained with the historic parametric method as described earlier and with the use of the CLIM94 (Climent et al, 1994) attenuation relation. Maps from regional agencies contained in this volume, with the exception of the Caribbean, have been compiled from results obtained with their respective versions of the source zone method as described by them in subsequent volumes of this final report. All maps presented in this volume have been compiled using the SURFER (Copyright Golden Software in Golden, CO, USA) mapping system following the specifications laid down by the Steering Committee for IPGH-produced maps.

In using the CLIM94 attenuation relation, we accept that the peak values may be lower than those obtained with laws suggested by other regional representatives, but results obtained with other attenuation laws would likely be subject to other criticism. In adopting the CLIM94 relation we reiterate that several individuals from within the project area agree with this decision.

In this portion of the report we first present regional results and comparisons, demonstrate the necessity to use local presentations and finally present a probabilistic seismic hazard map for the entire project area along with what is here termed a "one-time maximum" map of PGA compiled from a grid of the largest accelerations experienced at points throughout the project area due to a single event throughout the life of the catalogue (about 500 yr).

All maps in this volume have been compiled assuming solid rock or equivalent as the medium for which the computed PGA applies. In addition to the smoothing realized from the use of random numbers, the maps compiled independently by IPGH have also been smoothed within SURFER during the gridding and contouring processes. The grids provided by the regions have been smoothed during the contouring process only.

As is the case elsewhere in this volume the phrase "seismic hazard" is used in the sense of "probabilistic seismic hazard".

Regional representations and comparisons

Table 5 gives the results of a comparison of mean values for each seismic hazard level of the grids for Mexico as computed by UNAM using the source zone method and by IPGH using the historic parametric method. The agreement of the mean values for the four lower levels of seismic hazard is very good, but that for the fifth or highest level agrees well in terms of the mean value, but not in terms of the number of grid points with values within this range of PGA.. In this latter case there are only 32 values within the IPGH grid above the value of 500 gal whereas the UNAM grid contains 84, i.e., is greater by a factor of about two and one-half. The likely explanation would seem to be the use of different attenuation relations for the computations and the two methods of computing seismic hazard (the source zone method assumes a maximum earthquake that is "smeared" over the whole of the particular zone and thus could tend to emphasize the "high" hazard values more) Despite this, we can conclude that for México the IPGH grid appears to give a good representation of the general level of seismic hazard.

Table 5
México
Comparison of UNAM and IPGH Gridded Seismic Hazard Values
Return period = 500 yr

Value	UNAM Grid			IPGH Grid		
gal	Number of Grid Values	Average gal	RMS Dispersion gal	Number of Grid Values	Average gal	RMS Disersion gal
>500	84	632	84	32	627	103
250-500	172	334	70	219	327	62
125-250	248	185	37	362	177	35
62.5-125	294	88	17	369	90	19
<62.5	1,892	14	17	1708	19	15

Figs. 15 and 16 show versions of seismic hazard maps for México respectively based on the grid provided by UNAM and that computed by IPGH using its version of the historic parametric method. The UNAM map in Fig. 15 shows the PGA values to be confined to a relatively narrow belt along the west side of the country. When compared to the results shown in Fig. 16, several similarities and differences emerge:

- the IPGH map shows a slightly broader belt of linear seismic hazard values along the western part of the country with a much sharper "elbow" in the latitude range of 20-24^{0}N - this elbow is a manifestation of the Rivera Plate, a small plate that has all but disappeared, referred to by Zúñiga et al (1997) in Volume 2 of this series. See also Singh et al, 1985 for more discussion on the tectonics of this plate,

- the IPGH map shows variously shaped patterns to the west and east of the continous belt of seismic hazard values (one of which is located in the USA and not of interest here) not found on the map compiled from data provided by UNAM,

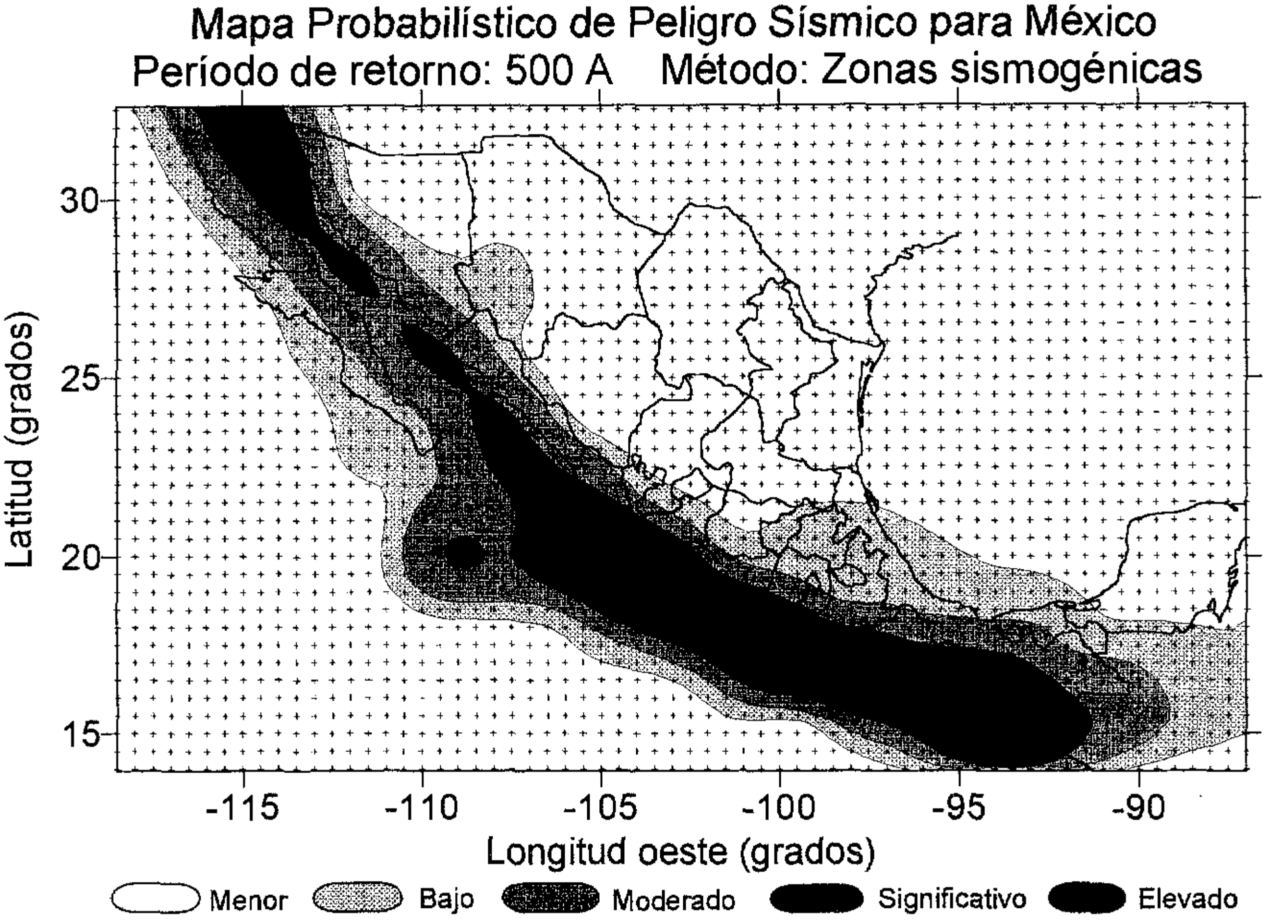

Figure 15. Probabilistic seismic hazard map for México for solid rock or equivalent compiled from data provided by UNAM. The plus signs indicate the points at which computations of seismic hazard have been made. Some smoothing applied during the contouring process.

- within the continuous belt along the subduction zone, both maps show the same levels of hazard values, with perhaps those on the map compiled from the UNAM data being slightly more frequent in the zone of "high" hazard.

A comparison of Figs. 16 and 17 shows clearly how the parametric historic method will mirror the distribution of the seismicity. The results using the source zone method are influenced by the distribution of source zones and, while the elbow appears in Fig. 15, it is much less pronounced.

The circular pattern shown in Fig. 16 in the southwest part of the map coincides clearly with a well defined pattern of seismicity (Fig. 17). This pattern is probably not present in Fig. 15 because the distribution of source zones probably not extend that far offshore. In the case of the other seismic hazard patterns in the eastern part of the map shown in Fig. 16, three possible explanations come to mind:

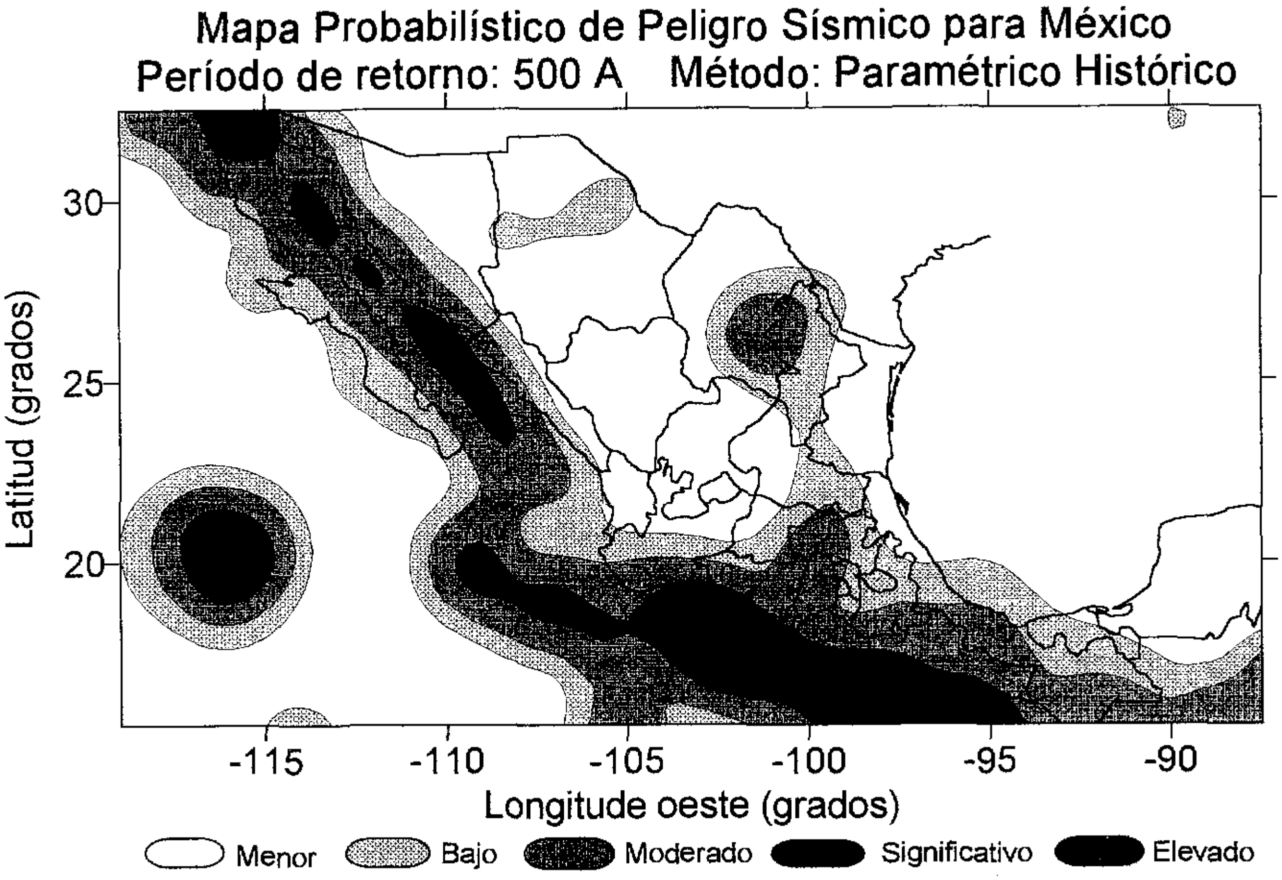

Figure 16. Probabilistic seismic hazard map of México compiled by IPGH from data computed with the historic parametric method developed for this project. The values of probabilistic seismic hazard have been computed for solid rock or equivalent.

- differences in the two methods of computing seismic hazard,
- *the use of different* attenuation relations - the CLIM94 relation used by IPGH does not attenuate as rapidly, and
- differences in the catalogues used.

The project catalogue has been compiled from a combination of data provided by UNAM supplemented by events in the ISC catalogue Copies of the project catalogue have been distributed to the regions, but no comments have been received as to differences with regional and local catalogues . This possiblity should be looked into in the near future to be certain the differences are real. We note the situation is similar with respect to the other regional catalogues.

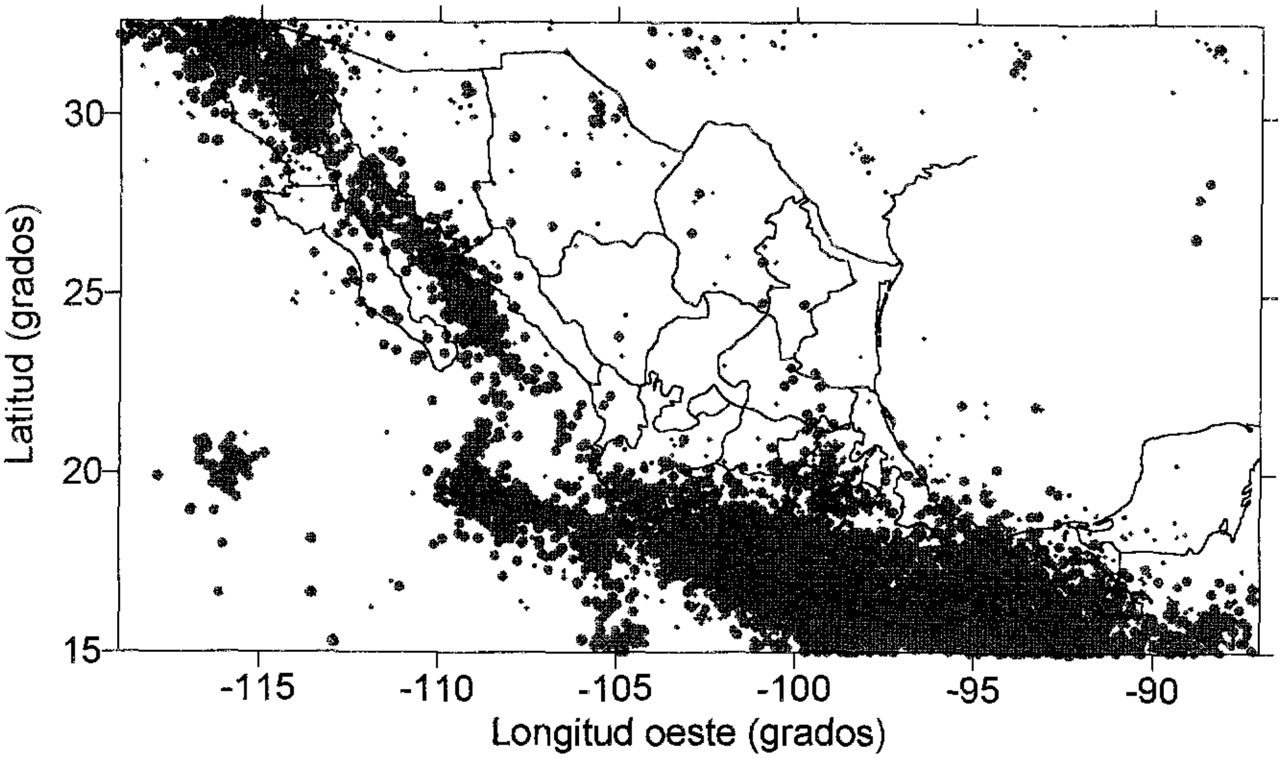

Figure 17. Distribution of seismicity in the period 1964-1993 in México as recorded in the project catalogue. The size of the dot is proportional to the magnitude of the event.

Table 6 shows that the mean seismic hazard values for the five zones of hazard in Central America agree very well in the lower three levels, less well in the fourth or second highest and not at all in the fifth or highest level. This highlights a concern that surfaced in the last meeting of the Steering Committee about the overall lower level of the seismic hazard values in Central America when compared to those of adjacent regions in México and South America. As the IPGH values were also calculated using the CLIM94 attenuation relation, the lower values in the ECG-UCR grid cannot be explained by differences in attenuation. Perhaps the source zone model and the recurrence relations within some or all of the source zones (possibly due to differences in the catalogue) could be possible explanations of the difference.

Table 6
Central America
Comparison of ECG-UCR and IPGH Gridded Seismic Hazard Values
Return Period = 500 yr

Value	ECG-UCR Grid			IPGH Grid		
gal	Number of Grid Values	Average gal	RMS Dispersion gal	Number of Grid Values	Average gal	RMS Dispersion gal
>500	0	0	0	4	627	62
250-500	170	329	45	215	348	66
125-250	268	182	31	232	184	66
62.5-125	89	96	17	93	99	17
<62.5	32	49	10	15	51	5

The results might also be affected by the different procedures used to compute the distance to the target point when calculating the PGA for a given earthquake. Whatever is the cause, some reconciliation of these differences will be necessary in the event of any major economic development in the boundary area of Central America with either México or South America.

Figs. 18 and 19 show probabilistic seismic hazard maps for Central America compiled from data computed by ECG-UCR by means of the source zone method and by IPGH using the historic parametric method. A comparison of the two diagrams suggests the following:

- the general shape of the contoured map is much the same in both cases, with any variations likely due to differences in the two methods
- the general level of seismic hazard on the map compiled from ECG-UCR data is lower than that of the IPGH map (see also Table 7 and the related discussion above) - for example, there is no zone of "high" hazard on the map compiled from ECG-UCR data,
- the sharp nearly east-west trend so prominent in the IPGH-based map is broader on the ECG-UCR-based map.

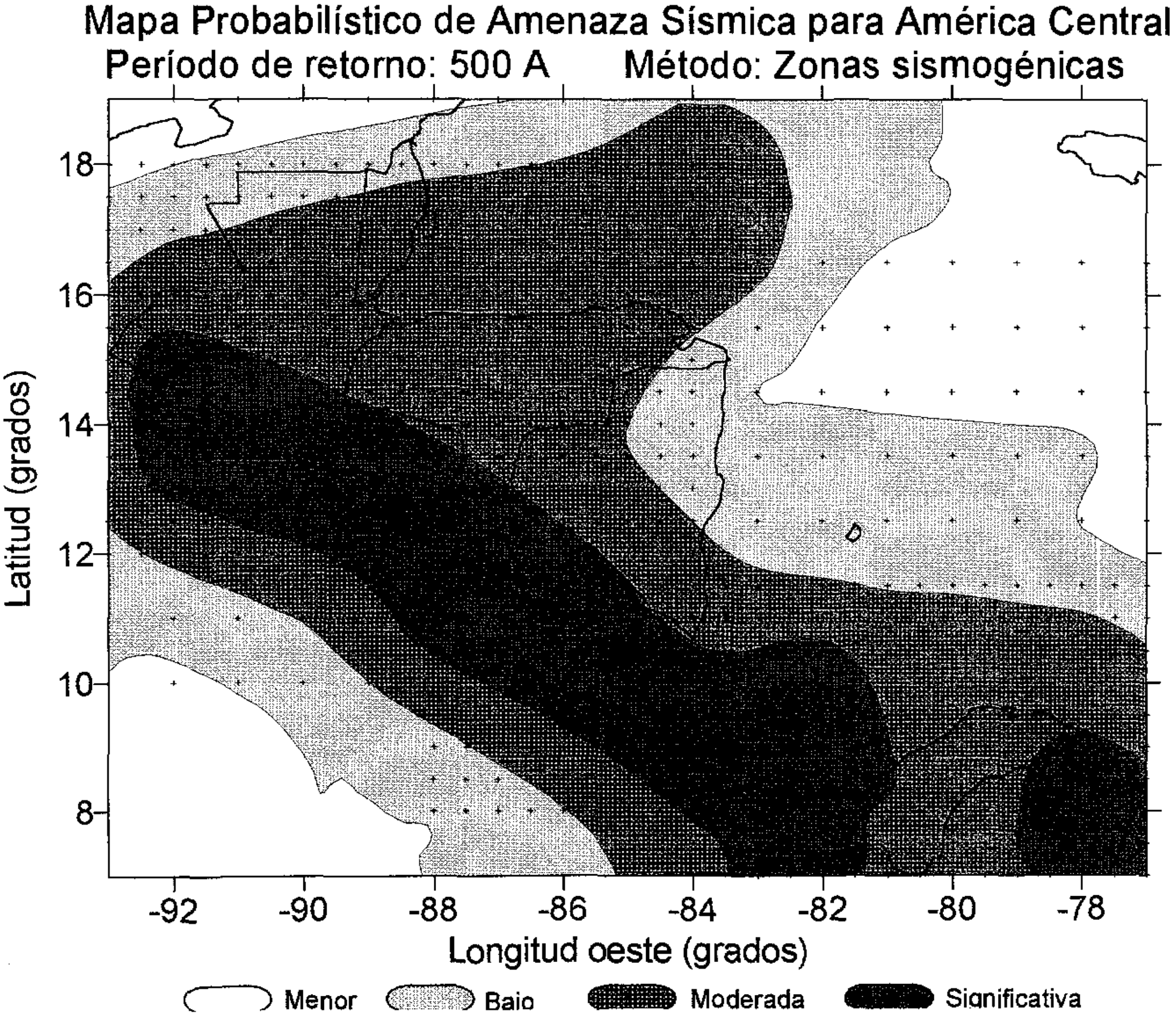

Figure 18. Probabilistic seismic hazard map (solid rock or equivalent) for Central America compiled from data provided by ECG-UCR and computed using the source zone method, the CLIM94 attenuation law and a computer programme provided by NORSAR. The plus signs indicate the locations for which data have been computed.

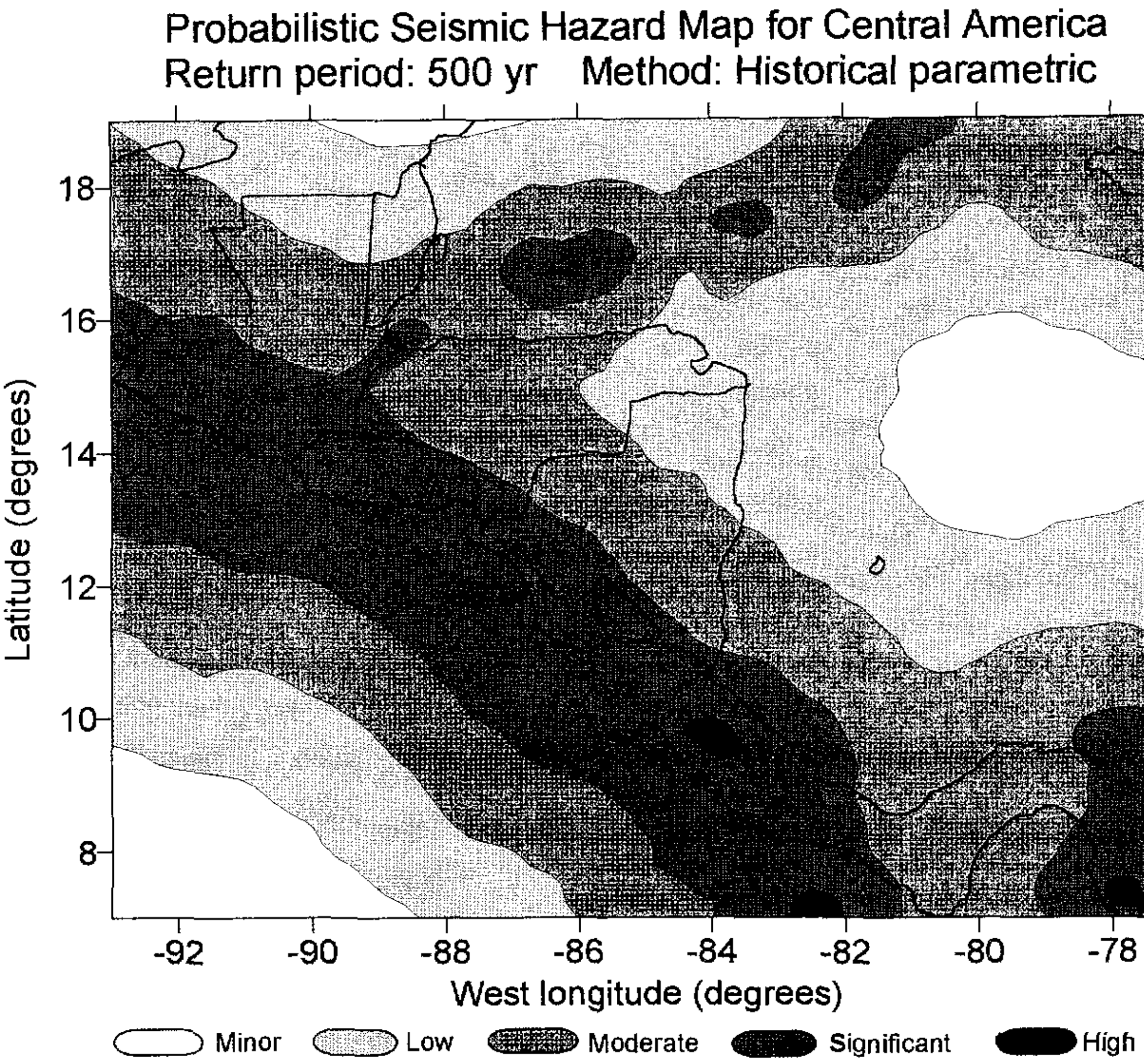

Figure 19. Probabilistic seismic hazard map for Central America computed and compiled by IPGH according to the specifications laid down by the Steering Committee. The CLIM94 attenuation law was used to compute seismic hazard estimates for solid rock or equivalent on a 0.5^0 grid.

Table 7 provides a comparison of the levels of seismic hazard computed by independent means in South America by CERESIS and IPGH. This table suggests that in terms of mean level the IPGH computed values of seismic hazard (i.e., before any processing to compile a map) agree well with those of CERESIS values throughout the entire range of seismic hazard values. The comparison at the high end of the range of seismic hazard (i.e., above 500 gal) is not as robust as that for the other ranges, but also does not suggest any cause for concern.

Table 7

Comparison of CERESIS and IPGH Gridded Seismic Hazard Values

Return Period : ~500 yr

Value	CERESIS Grid			IPGH Grid		
gal	Number of Grid Values	Average gal	RMS Deviation gal	Number of Grid Values	Average gal	RMS Dispersion gal
>500	25	567	46	21	617	83
250-500	163	337	68	235	335	59
125-250	267	180	35	250	185	35
62.5-125	103	102	11	52	107	12
<62.5	0	0	0	0	0	0

Figs. 20 and 21 show respectively the maps compiled from data provided by CERESIS and IPGH. Fig. 20 has been compiled by CERESIS from results provided by each of the member countries using attenuation laws that varied with the country. Comparison of the two maps suggests the following:

- the pattern on this CERESIS-based map is not as broad as that of IPGH,
- there is more area of "high' seismic hazard on the CERESIS map than on the IPGH map,

On several occasions seismologists from South America have noted the difficulty of gaining a good understanding of attenuation of seismic waves within this vast region. Explanations for such things as the high rate of attenuation beneath the Andes, at least in the Chile-Argentina region, have yet to be found. Despite continuing efforts seismologists from the region often refer to the difficulties of getting good strong motion records and leave the impression that it could be some time before they acquire enough data to carry out a thorough study.

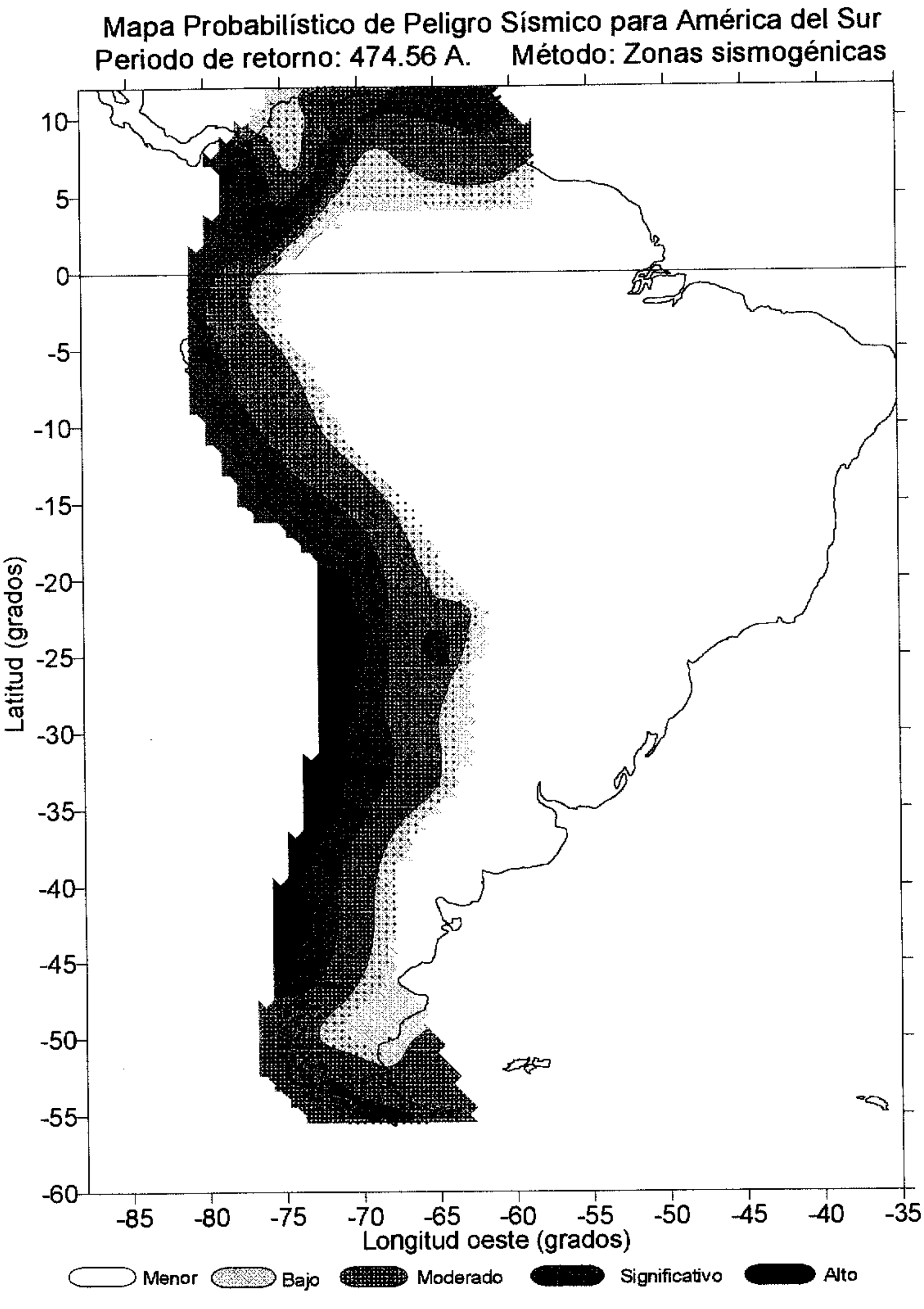

Figure 20. Probabilistic seismic hazard map for South America (solid rock or equivalent) compiled from gridded data supplied by CERESIS. The dots indicate the points for which seismic hazard estimates have been calculated. Although the contouring extends beyond the limits of the computed points in places, it is only valid within their bounds.

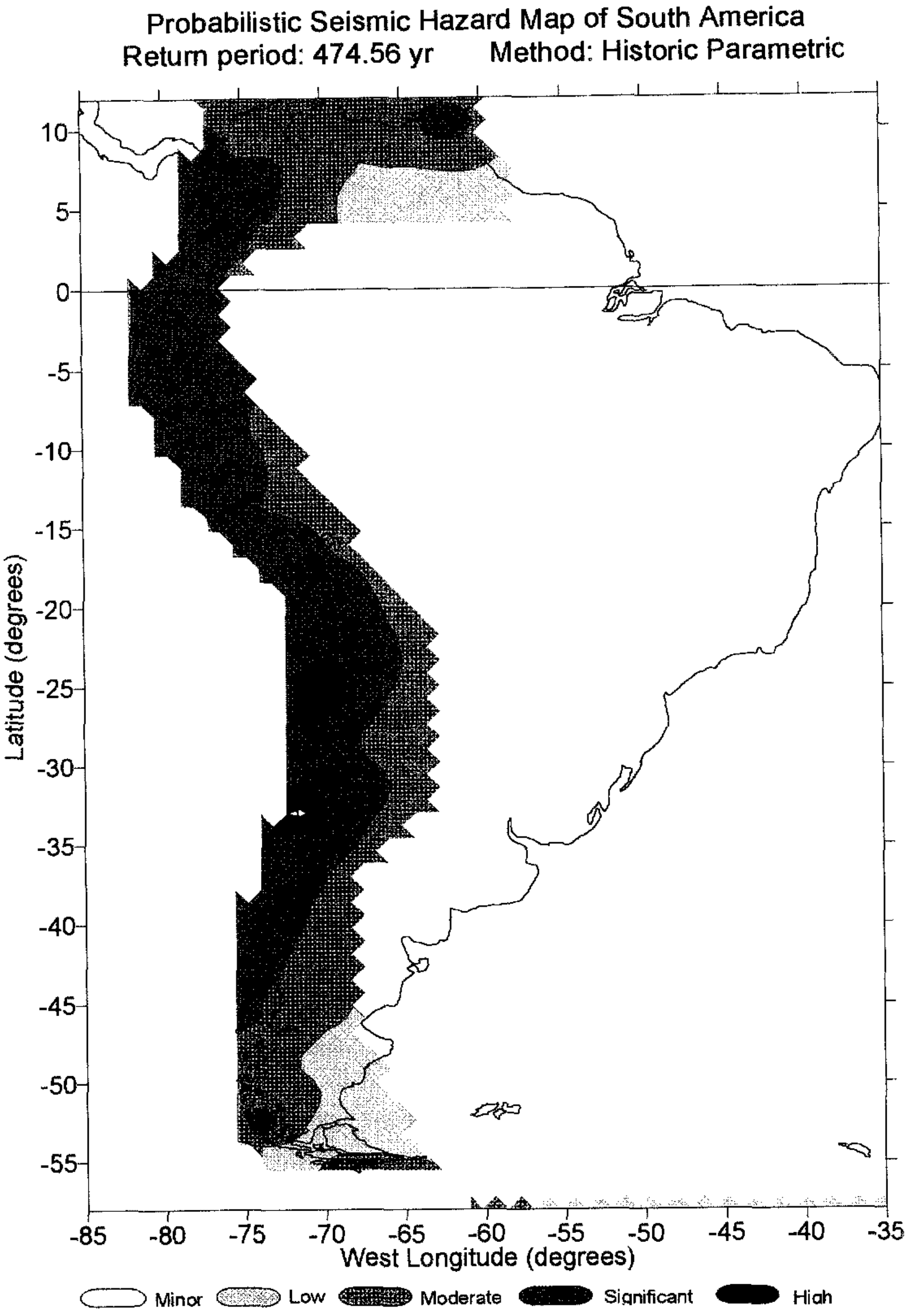

Figure 21. Probabilistic seismic hazard map for South America (solid rock or equivalent) compiled from data computed by IPGH. The contoured map has been compiled from data computed on the same grid as Fig. 20 and cliipped using the same function.

The differences in level of hazard take place mainly at the high end of the seismic hazard spectrum and have been confirmed by looking at some of the gridded values. A number of possible explanations have already been suggested in the discussion of the maps from other regions. One of the most plausible is the CLIM94 attenuation law used for the computations by IPGH gives the lowest peak or maximum values of all the relations suggested by the regional representatives (see Fig. 10 which shows all the relations for a hypothetical earthquake of M = 8 and depth equal to 50 km - calculations for other earthquake magnitudes indicated this difference decreased with smaller magnitudes). Differences may also be explained, wholly or partly, by the use of different methods of computing seismic hazard, one of which is more interpretative (source zone) and therefore influenced by the ideas of the individuals responsible for the defining the distribution of source zones.

We conclude this section with a comparison of the results for the Caribbean. The IPGH values have been computed in the usual way with the JB93 and CLIM94 attenuation relations used respectively for earthquakes located at depths greater than and less than 15 km. The regional values for the Caribbean have been provided by McQueen, 1997 who carried out an evaluation of seismic hazard in the Caribbean using three different probabilistic methods of seismic hazard estimation. The methods she used are the source zone or Cornell-type (two different computer programmes), the extreme value method (Gumbel, 1958; Makropoulos and Burton, 1986) and the historic parametric method as described in this report. In her evaluation of the results she found all methods gave similar results, but concluded that the historic parametric method seemed more stable under varying conditions of computation. We therefore follow her recommendation and use the results she obtained with the historic parametric method as the basis for comparison.

The procedures for the calculation of the grid provided by McQueen, 1997 differed from the practices adopted here in the following respects:

- the JB93 and WC82 attenuation relations have been used respectively for events less than and greater than 15 km,

- the values at each grid point have been determined from 25 iterations using random numbers to scale the estimated uncertainties of all parameters used in the calculations.

The regional probabilisitic seismic hazard map for the Caribbean is given in Fig. 22 and the corresponding map produced by IPGH in Fig. 23. The patterns of seismic hazard in the two maps are generally the same as are the peak levels of seismic hazard. They differ, however, for the lower levels of seismic hazard. The regional map in Fig.22 does not show any values within the range of seismic hazard that is here called "minor" (i.e., <62.5 gal) whereas the IPGH map shows significant areas at this level. This can be seen more clearly in Table 8 which shows the regional results of McQueen, 1997 contain no values in the range of "minor" hazard. The explanation of this difference almost certainly lies in the differences of behaviour of the CLIM94 and WC82 attenuation relations. The WC82 relation does not attenuate as rapidly as does CLIM94 (see Fig. 10) and therefore we can expect the ground effects of the earthquakes in the Caribbean (many of which have an inermediate to deep focal depth) to extend to a much greater distance.

Table 8
Comparison of Seismic Hazard Results for the Caribbean
Return Period: ~475 yr

Range	Regional Grid (McQueen, 1997)			IPGH Grid		
gal	Number of Events	Average Value gal	RMS Dispersion gal	Number of Events	Average Value gal	RMS Dispersion gal
>500	2	522	6	1	524	0
250-500	84	330	62	54	320	54
125-250	216	177	35	171	176	33
62.5-125	162	100	16	132	91	18
<62.5	0	0	0	106	42	13

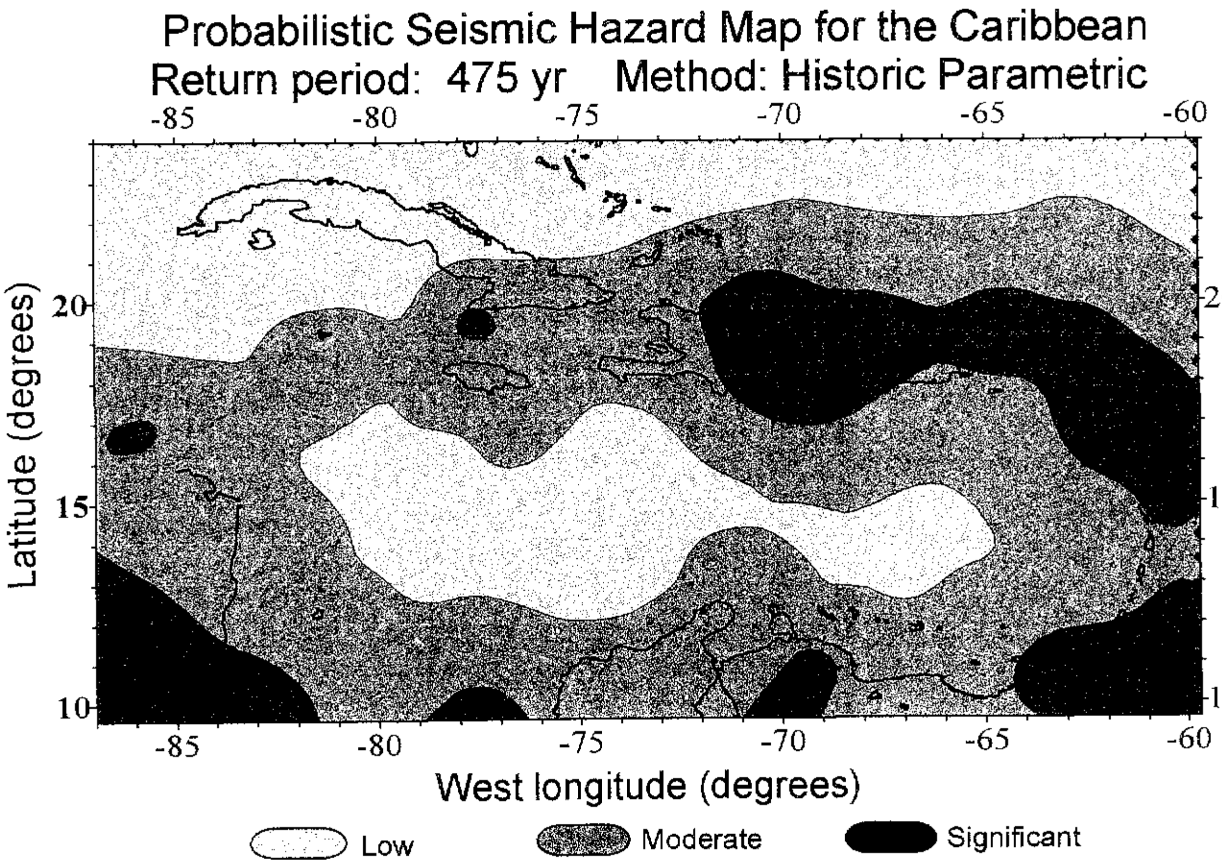

Figure 22. Probabilisitc seismic hazard map of the Caribbean compiled for the gridded values provided by McQueen, 1997. The computations were made at intervals of 0.2° with each value determined from 25 iterations using random numbers to scale estimated uncertainties of all earthquake parameters used in the calculations.

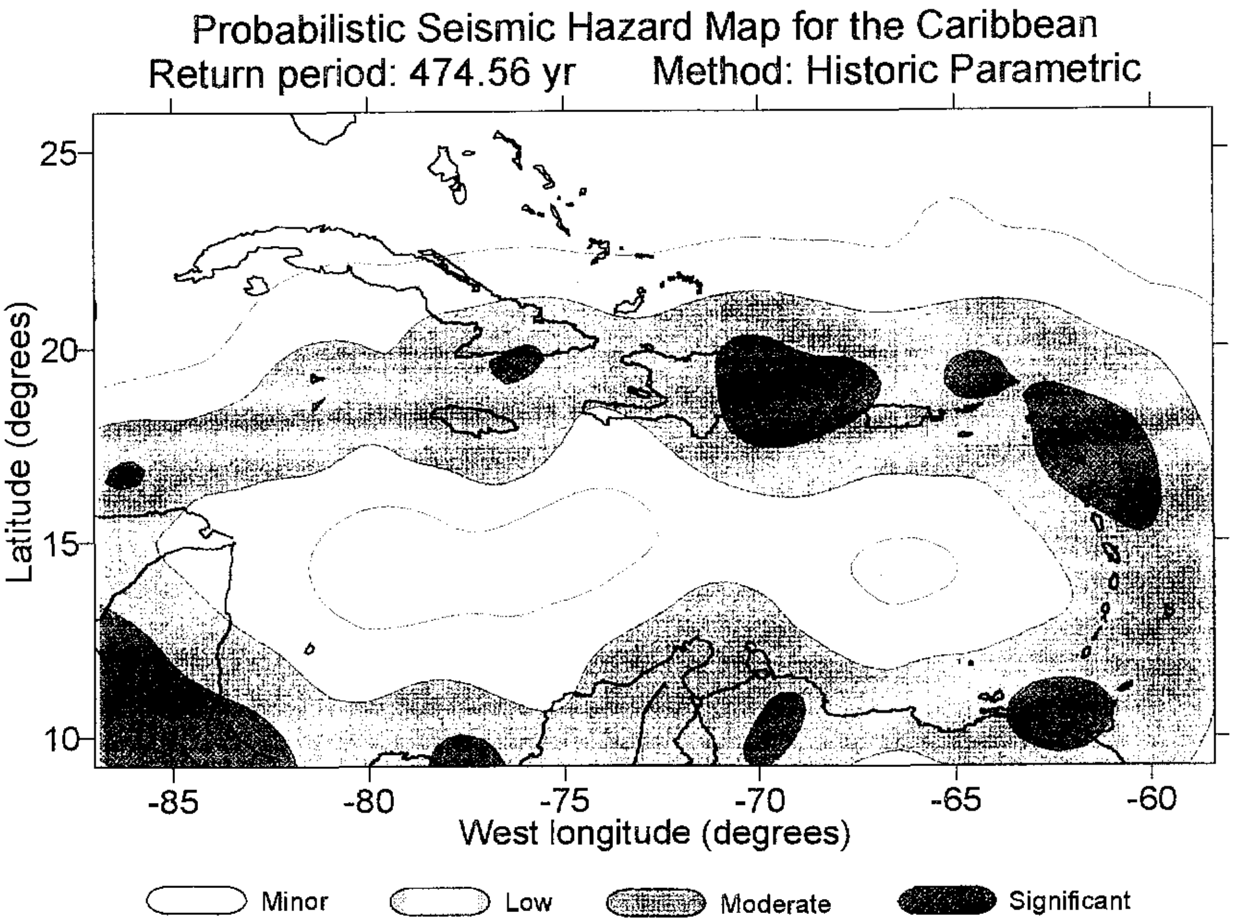

Figure 23. Probabilistic seismic hazard map for the Caribbean compiled from data provided by IPGH for solid rock or equivalent. The grid interval is 0.25^0 - all values detemined after 100 iterations using random numbers to scale estimated uncertainties in earthquake parameters.

The observant reader will also note that a "seam" exists between the regional results for Central America (Fig. 18) and the Caribbean (Fig. 22). McQueen, 1997 resolved these differences.

Local representations

Fig. 23 shows a seismic hazard map of the Caribbean compiled to the specifications of the Steering Committee. Attention is drawn to the island of Jamaica in the central west part of the map, south of the eastern end of the Island of Cuba. According to the map in Fig. 23 the entire island is covered by the same level of hazard (called "moderate" in this report). However. Fig.24 shows the presence of a quasi-circular zone of hazard values falling within the level called "significant" in this report. This area of "significant" hazard is about one-half degree square and is located over the eastern end of the island.

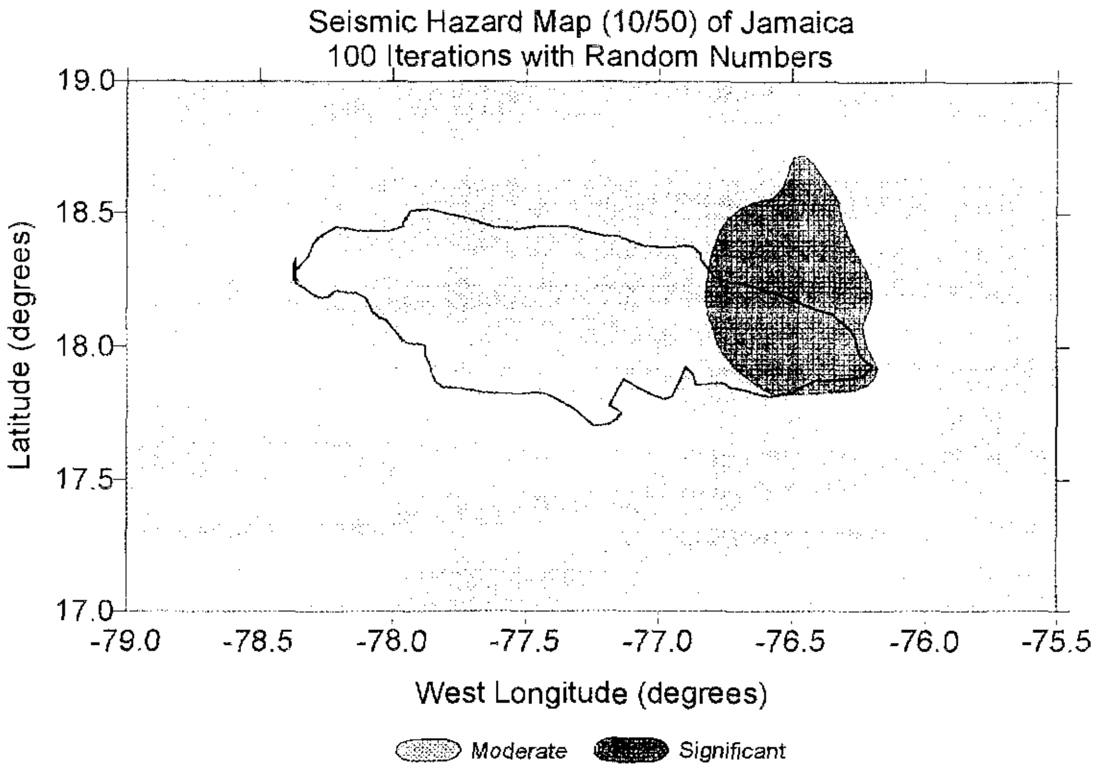

Figure 24. Seismic hazard map (solid rock or equivalent) of the island of Jamaica computed by the historic parametric method at a grid interval of 0.1^0 from the IPGH catalogue. The values at grid points were detemined after 100 iterations using random numbers to scale estimated uncertainities of parrameters used in the calculations.

In Fig. 23 the hazard values used to compile the map were computed at 0.25^0 intervals as compared to 0.1^0 for those for Fig. 24. Depending on where the points in the regional grid fall, there could be only two or three of them located within the area which would make any values in the "significant" range good candidates for elimination by the smoothing used in SURFER during the gridding and contouring processes.

The difference in the two maps demonstrates the necessity of computing a more detailed grid to provide the fullest possible view of seismic hazard when faced with the need to provide advice to authorities responsible for setting building codes or criteria for the construction of large engineered structures.

Project Area Maps

Table 9 shows a comparison of the hazard values computed on a one-degree grid for the project area with those at common grid points in México, Central America and South America. Although the IPGH computations were made using a return period of 474.56 yr, the values at grid points in common with those in México and Central America have been adjusted to a return period of 500 yr. At first glance this table might appear redundant to Tables 5 to 8. However, this IPGH grid has been computed independently of the IPGH grids used for the regional comparisons and a good comparison would confirm the regional results.

Table 9

Comparison of One Degree-spaced Seismic Hazard Values for the Project Area with those for México and Central and South America

Range	México and Central and South America			IPGH		
gal	Number of Events	Average Value gal	RMS Dispersion gal	Number of Events	Average Value gal	RMS Deviation gal
>500	46	598	75	27	587	100
250-500	256	335	64	296	334	61
125-250	409	182	34	439	186	36
62.5-125	211	96	16	263	94	18
<62.5	535	14	17	432	22	18

Like those for Tables 5 - 8 the comparison shown in Table 9 seems excellent, with the largest difference being the number of "high" hazard values - 27 in the IPGH grid as opposed to 46 in the combined regional grids. The best explanation would appear to involve some combination of differences in the methods of computing seismic hazard and in the attenuation relations employed, although we emphasize that in the case of Central America the attenuation relations are the same for both grids.

Tables 5 to 9 show only the mean values for each zone without regard to their distribution - that is, each set of mean values has been computed without reference or comparison to individual values in either grid. Figs.15, 16 and 18-23 compensate this shortcoming to some extent through their visual presentation of the distribution of seismic hazard throughout the region, although varying degrees of smoothing could distort this comparison to some extent

A different perspective on the comparison of results can be provided by computing mean differences (regional minus IPGH values) for individual grid points within each range of seismic hazard and for the area as a whole. These results are given in Table 10 which shows a much more variable comparison. Several observations stem from the results shown in this table:

- the positive differences in the two high ranges and the negative differences in the lower ranges would tend to confirm the results of Fig. 10 which shows that the CLIM94 attenuation relation gives lower PGA (for larger events at least) near the epicentre and, with the exception of the Kausel and Woodward-Clyde relations, attenuates more slowly than the others,

- part of the explanation for the pattern of positive and negative differences may lie in the smoothing due to the use of random numbers,

- individual differences at grid points can evidently be quite large if the RMS deviation is any indicator, but this might be expected because of differing methods of computing seismic hazard, the various attenuation relations used and the use of random numbers by IPGH,

- despite some large differences at individual grid points throughout the project area the overall mean difference for the project area is within 10 gal of zero,

- given the disparity in the properties of the attenuation relations and the difference in the methods used to compute seismic hazard, the agreement between the IPGH grids and those provided by the regions, as expressed by the average of differences at all grid points, does suggest that the IPGH grid gives a fair representation of the overall level of seismic hazard.

Table 10

Mean Differences between One-degree Gridded Values for Project Area and those for México and Central and South America

Range gal	Number of Events	Mean Difference gal	RMS Dispersion gal
>500	46	197	132
250-500	256	30	85
125-250	489	-20	85
62.5-125	211	-29	66
<62.5	535	-33	61
All	1537	-10	70

Although the results equivalent to those of Table 10 have not been shown for each of the regions, comparisons of the IPGH grid with those for México and South America show a pattern similar to that of Table 10. The same is not true for Central America where, in all ranges, the mean differences are strongly negative (i.e., seismic hazard values for Central America are consistently lower despite the use of the same attenuation relation by IPGH). This confirms the results of other comparisons and while this does not demonstrate the Central American results are in error, it does indicate that future investigations should concentrate in part on the reason for this circumstance.

Fig. 25 shows the probabilisitic seismic hazard map, for solid rock or equivalent, for the project area compiled from the same one-degree grid used for the summaries of the IPGH contribution to Tables 9 and 10. Like the IPGH maps presented earlier, the data used to compile this map have been smoothed in three separate stages: first by the use of pseudo-random numbers during the computation of the original grid, second by matrix smoothing in SURFER during the compilation of the plotting grid and third during the contouring process of SURFER.

Although Table 9 indicates the presence of values of what are here classified as "high" seismic hazard, they have been removed by SURFER in the process of smoothing the grid and contouring the map. However, it turns out that the peak values on the smoothed grid used to compile the map are just on or below that of the lower boundary value for the "high" seismic hazard range.

On several occasions, individuals involved with the project, either expressed interest in or produced some version of what is called here a "one-time maximum" map of a particular earthquake-related parameter. Early in the project, maps of maximum intensity due to a single event were published in the annual reports, but later the interest turned toward maps of one-time maximum PGA experienced at any point in the project area.. This interest has developed because the catalogue now covers a span of about 500 yr, which is approximately the return period used for most probabilistic seismic hazard estimates. Even though this catalogue is by no means complete, most or all of the largest events have probably been logged into it and there is interest in seeing how this "one-time maximum" map compares with probabilistic seismic hazard.

Fig. 26 shows the "one-time maximum" PGA for solid rock or equivalent due to a single event computed on a grid throughout the project area using the CLIM94 attenuation relation. The patterns of contours on this map resemble those of the probabilistic seismic hazard map (Fig. 25), but the PGA values are lower. This map shows the contoured levels of one-time maximum PGA experienced (as estimated using the CLIM94 attenuation relation and iterating 10,000 times with random numbers) throughout the project area over the last 500 years, but does not predict in any way what might be experienced in any location over any period of time. Therefore this map, while interesting, has no meaning in a probabilisitic sense.

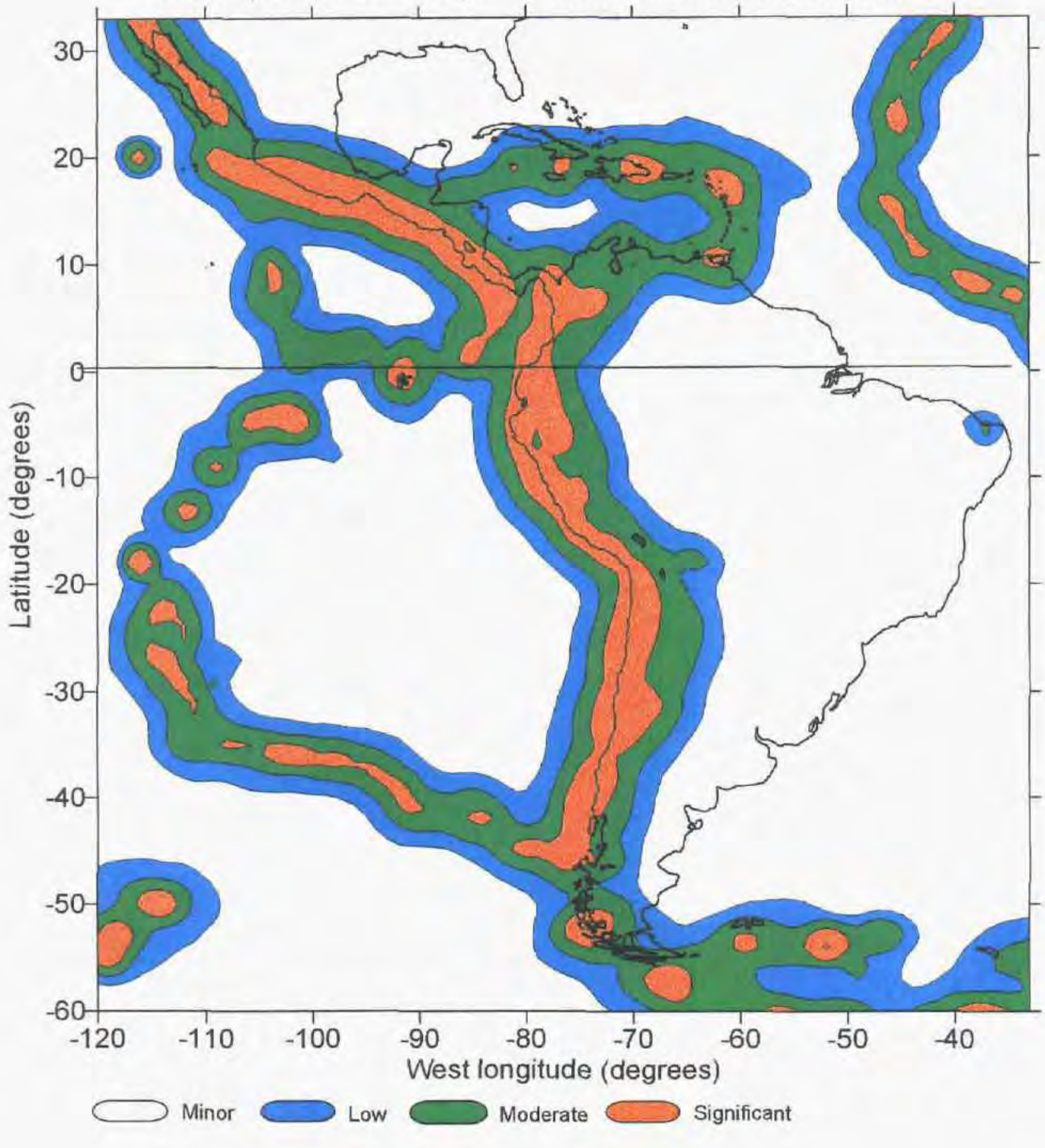

Figure 25. Seismic hazard map (solid rock or equivalent) of the project area computed from the IPGH catalogue using the CLIM94 attenuation law (Climent et al, 1994). .The grid interval for the computations is one degree (1^0). All values determined after 100 iterations using random numbers to scale estimated uncertainties iin all parameters used for the calculations.

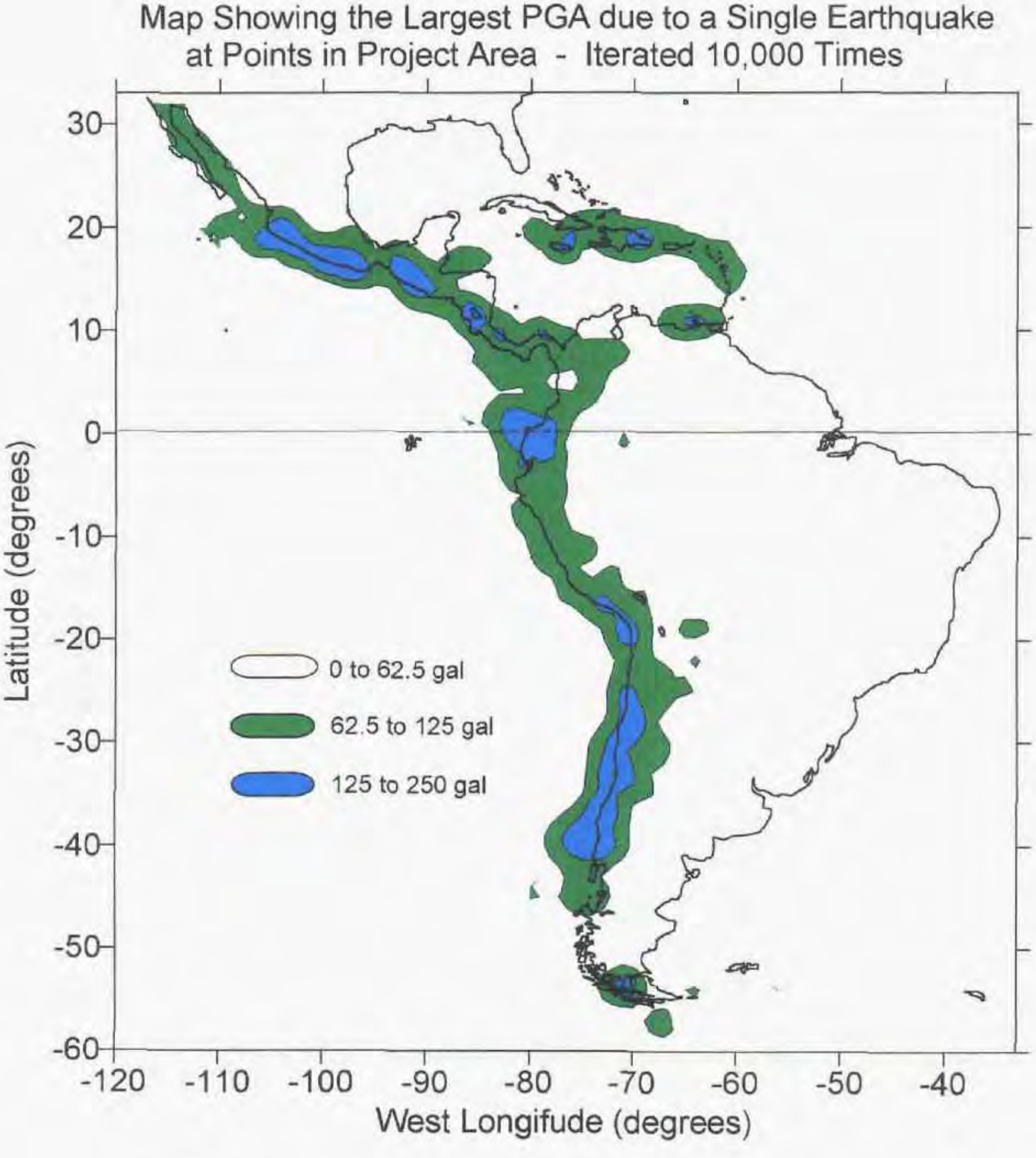

Figure 26. Map showing the largest PGA (solid rock or equivalent) due to a single event at points throughout the project area. The data used to compile the map have been computed (using the CLIM94 attenuation relation) from the IPGH catalogue on a one degree grid. Values detemined from *10,000* iterations with random numbers to scale estimated uncertainties in earthquake parameters used for the calculations.

Conclusions

1. The method of extrapolation of the observed data computed with the historic parametric method is central to the results obtained. We have chosen a method embodying the idea of the extrapolation process being asymptotic to a maximum possible value rather than some other method such as a power law fit. This approach yields results that are lower or less conservative than other methods, but would appear justified on nothing other than common sense.

2. There is nothing subjective about the application of the historic parametric method - the earthquakes selected from the catalogue speak for themselves via the appropriate attenuation relation - i.e., there is no requirement to group them according to tectonic concepts, patterns of seismicity or other criteria.

3. The Gutenberg-Richter equation is assumed to apply to all earthquakes, small and large. This may not be true. Many seismologists (see for example, Scholz, 1990 for a discussion) believe that earthquakes large enough to crack right through the rigid part of the lithosphere may not follow the same recurrence relationships as the smaller events. If this is so, the rate of recurrence of larger events can not be predicted by this method.

4. The assumption that earthquakes occur randomly in time is one that needs examination. Clearly, the occurrence of foreshocks and aftershocks ensures that earthquakes cluster in time to some extent at least. Also, calculations for locations within zones that are generally active seismically and have shown low levels of activity in the past, but may show higher levels in the future, will give misleading results using the historic parametric method.

5. The attenuation relation used for the computations for the IPGH maps has been chosen from a list specified by the Steering Committee: a list which reflects regional preferences. This list is not regarded as the last word on the topic and we hope that attenuation laws better representing the true situation will be developed in the future. Some detail of the attenuation laws used regionally can be obtained from their reports on seismic hazard which appear as part of this series. Our conclusion here would be the obvious:

- reliable attenuation relations are critical to the calculations and uncertainties in them are by far the largest source of error in the computations,

- much more research and many more strong motion records are required before we can be satisfied that we understand the attenuation of seismic waves throughout the project area - this is not to suggest the attenuation laws used here are incorrect, but rather they must be subjected to considerable further evaluation,

- the attenuation law determined by Climent et al (1994) for Central America has proved useful for this work and it (along with the Boore et al (1993) relationship) is the best documented to date of those available for the project area.

6. Comparisons with the regional seismic hazard estimates both in tabular and map form generally confirm that the IPGH map provides a good reference level for seismic hazard throughout the project area. The somewhat lower hazard values in Central America as compared to the results obtained by IPGH, México and South America need to be investigated to determine their cause. The absence of a narrow zone of "high" hazard along the west coast in Chile is not regarded as serious as the smoothed gridded IPGH results sit on the border between the zones of "high" and "significant" hazard (500 gal).

7. We need to move on to the next phase of seismic hazard , the so-called spectral seismic hazard. Climent et al (1994) have computed a spectral version of their attenuation law and its use would appear a good place to start in this next phase. This is an urgent task as GSHAP has decided to go this route in a schedule that calls for completion of a first global seismic hazard map in about two years.

8. In an area which contains some of the most active and fastest moving plates observed anywhere on the globe, funds are needed to purchase digital seismographs and GPS receivers to be co-located at critical points throughout the project area to assist in improving our understanding of seismicity, seismic hazard and attenuation of seismic waves in greater detail. Most countries in the region have the trained personnel and institutes capable of operating such equipment, but many lack the funds to purchase this equipment which for reasons of economy, efficiency and quality of results should be standardized. Therefore, the financial help of agencies such as IDRC is still needed despite the generally improving conditions in the area.

Conclusiones

1. El método de extrapolación de los datos observados, usando el método paramétrico histórico, fue básico para los resultados obtenidos. Escogimos el uso de un método que incorporaba la idea de un proceso que es asimptótico a un valor máximo posible, en lugar de algún otro método como un ajuste a una ley de potencias. Este enfoque proporciona resultados que son menores o menos conservadores que otros métodos, pero parecen justificados sobre todo en el sentido común.

2. La aplicación del método paramétrico histórico no tiene nada de subjetiva - los sismos seleccionados del catálogo hablan por sí mismos vía la relación de atenuación apropiada - i.e. no se requiere agruparlos de acuerdo a conceptos tectónicos, patrones de sismicidad u otros criterios.

3. Se asume que la ecuación Gutenberg-Richter se aplica todos los sismos, grandes o pequeños . Esto puede no ser cierto. Muchos sismólogos (ver por ejemplo, Scholz, 1990 para una discusión) creen que los sismos suficientemente grandes como para romper a través de la parte rígida de la litósfera no siguen las mismas relaciones de recurrencia de los sismos pequeños. Si esto es así, la tasa de recurrencia de los eventos mayores no puede predecirse por este método.

4. La suposición de que los sismos ocurren aleatoriamente en el tiempo debe ser examinada. Claramente, la existencia de precursores y réplicas prueba que, en cierto sentido, existe una acumulación temporal de los sismos. Al mismo tiempo, los cálculos usando este método, para localidades dentro de zonas que son en general sísmicamente activas y que han mostrado bajos

niveles de actividad en el pasado, pero que pueden tener mayores niveles en el futuro, pueden conducir a conclusiones erróneas utilizando el método paramétrico histórico.

5. La relación de atenuación utilizada para calcular los mapas del IPGH fue seleccionada de una lista especificada por el Comité Directivo: una lista que refleja preferencias regionales. Esta lista no debe considerarse como la última palabra sobre el tema, y esperamos que en el futuro se desarrollen leyes de atenuación que representen mejor la situación real. Pueden obtenerse detalles de las leyes de atenuación utilizadas de los reportes regionales sobre peligro sísmico que aparecen como parte de esta serie de reportes finales. Nuestras conclusiones aquí son las obvias:

- tener relaciones de atenuación confiables es básico para los cálculos, y las incertidumbres en ellas son, con mucho, la mayor fuente de error en los cálculos,

- se requiere mucho más investigación y muchos más registros de movimientos fuertes en el área del proyecto antes de que podamos sentirnos satisfechos de que entendemos la atenuación de las ondas sísmicas en el área del proyecto - no queremos sugerir que las leyes de atenuacióin usadas aquí sean incorrectas, sino que deben estar sujetas a evaluaciones futuras considerables,

- la ley de atenuación determinada por Climent et al (1994) para América Central, demostró ser útil para este trabajo, ya que es (junto con la relación de Boore et al (1993)) la mejor documentada a la fecha en el área del proyecto.

6. Las comparaciones con los resultados regionales tanto en forma tabular como en mapas confirman, en general, que el mapa del IPGH proporciona un buen nivel de referencia para peligro sísmico en toda el área de proyecto. Se requiere investigar los valores de peligro ligeramente menoras en América Central, en comparación con los resultados obtenidos por el IPGH, México y Sudamérica para determinar la causa. La ausencia de una zona angosta de alto peligro en la costa occidental de Chile no es considerada como seria, ya que los valores del IPGH en esa rejilla se ubican en la frontera entre los valores de peligro "alto" y "significativo" (500 gal) y son suavizados en el proceso de compilación.

7. Necesitamos movernos a la siguiente fase de peligro sísmico, el llamado peligro sísmico espectral. Climent et al (1994) calcularon la versión espectral de su ley de atenuación y basados en nuestros resultados, su uso parece ser un buen lugar para empezar la siguiente fase. Este es un trabajo urgente ya que GSHAP ha decidido seguir esta ruta en su camino a integrar un primer mapa de peligro sísmico global en aproximadamente dos años.

8. En un área que contiene algunas de las placas más activas y de movimiento más rapido observadas en cualquier lugar del globo, se requiere financiamiento para adquirir sismógrafos digitales y receptores GPS para colocar ambos en puntos críticos distribuidos en el área del proyecto y ayudarnos a mejorar nuestra comprensión de la sismicidad, el peligro sísmico y la atenuación de las ondas sísmicas en mayor detalle. La mayoría de los países de la región tienen personal entrenado e institutos capaces de operar estos equipos, pero muchos carecen de fondos para su adquisición, la que por razones de economía, eficiencia y calidad en los resultados debería

estandarizarse. Por lo tanto, aún se requiere el apoyo financiero de agencias como el IDRC, a pesar de que en general, las condiciones en el área están mejorando.

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APPENDIX I

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APPENDIX II

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APPENDIX III

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APPENDIX IV

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APPENDIX V

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APPENDIX VI

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APPENDIX VII

List of Addresses

The names and addresses given here are based on the attendance at the various workshops held throughout the life of the prject. The addresses, telephone numbers, etc. have been updated where the information is available, but any one wishing to contact any individual should be aware that the information may be out of date.

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APPENDIX VIII

The Format of the Epicentre Records in the Project Catalogue

Each record gives an epicentral estimate. Most fields in the record are optional - spaces in the field indicate that no value has been given.

Byte 1. (*) or ( ) - record type indicator - format=A1
    1. (*) inidcates the primary estimate of an event
    2. ( ) indicates an alternative or secondary estimate of an event

Bytes 2-7. Agency code - format=A6 - left justified
    Further details of the agency codes used in this catalogue may be found in Appendix IX.

Byte 8. Data source - data taken from the publication indicated.
    1. (B) - BCIS
    2. (I) - ISS/ISC
    3. (N) - NEIS
    4. (T) - Telex
    5. ( ) - Direct

Byte 9. UTC date - optional - Format A1
    (-) implies B.C. date
    ( ) implies A.D. date

Bytes 10. Time of origin - the MANAGE programme reads this as A15 and then divides.
    1. Bytes 10-13 - Year - format=I4
    2. Bytes 14-15 - Month - format=I2
    3. Bytes 16-17 - Day - format=I2
    4. Bytes 18-19 - Hours - format=I2
    5. Bytes 20-21 - Minutes - format=I2
    6. Bytes 22-24 - Seconds - format=F3.1

Bytes 25-30 - optional - format=F5.3, A1 - latitude in degrees - this field is terminated with a N or S.

Bytes 31-37 - optional - format F6.3, A1 - longitude in degrees - this field is terminated with a W or E.

Bytes 38-40 - optional - format=I3 or (***) - depth in kilometres - (***)= depth out of range.

Bytes 41-50 - optional - first magnitude

1. Bytes 41-43 - magnitude value - format=F3.2.
2. Byte 44 - magnitude scale - format=A1
    1. ( ) - unspecified
    2. (B or B) - body wave magnitude
    3. (C) - coda length magnitude
    4. (D) - duration magnitude
    5. (L) - local (Richter) magnitude
    6. (N) - magnitude from Lg phases (Nuttli)
    7. (S or s) - magnitude from surface waves
    8. (W or w) - moment magnitude
3. Bytes 45-50 - agency code for magnitude - left justified - format=A6.

Bytes 51-60 - optional - second magnitude - sub fields as for first magnitude.

Bytes 61-62 - optional - maximum intenstiy from 0 and 12 inclusive - format I2.

Bytes 63-64 - optional - intensity scale - format=A2
1. ( ) - unspecified
2. (CS) - Mercalli, Cancani and Seberg
3. (J) - Japanese Meteorology Agency
4. (M) - Mercalli
5. (MM) - Modified Mercalli
6. (RF) - Rossi & Ferel
7. (SK) - Medvedev, Sponheur & Karnik

Bytes 65-67 - given when latitude and longitude present - Flinn-Engdahl geographic region number - format=I3.
Flinn, E.A. E.R. Engdahl, 1965. A proposed basis for geographic and seismic regionalization. Rev. Geophysics, 3, 123.

Bytes 68-70 - optional - number of stations associated with determination - format=I3.

Byte 71 - type of event - format=A1
1. ( ) - earthquake
2. (C) - coal bump
3. (E) - non-nuclear explosion
4. (I) - implosion - collapse
5. (M) - meteoric source
6. (N) - nuclear explosion
7. (R) - rockburst
8. (X) - explosion of unspecified source

Bytes 72-74 - optional - used in place of 68-70 when it is not clear whether the number refers to number of stations reporting or number of stations used in solution - format=I3.

Byte 75 - optional - cultural factor - format=A1

1. (F) - felt earthquake
2. (C) - deaths
3. (X) - damage

APPENDIX IX

Agency Codes for Epicentral and Magnitude Determinations

ABE	Abé (1981 & 1984) - magnitudes of great earthquakes 1900-1984.
ACS	Acres International Ltd., 1961
AFL	Alvarado et al, 1988 (Appendix III)
ALQ	Alberquerque, New Mexico, USA.
ALV	Alvarado, 1993 (Appendix III)
AMB	Ambrayseys, 1994.
ARE	Arequipa, Peru
BAA	Buenos Aires, Argentina
BCIS	Bureau Central International de Sismologie, Strasbourg, France
BCX	Ensenada, Baja California
BDA	Bath and Duda, 1979 (Appendix II)
BGS	British Geological Survey
BHP	Balboa Heights, Panamá
BKS	Byerly, California, USA
BLA	Blacksburg, Delaware, USA
BMO	Blue Mountain, USA
BOG	Bogotá, Colombia
BRK	Berkeley, California, USA
CAR	Caracas, Venezuela
CARR	Carr and Stoiber, 1978 (see Appendix III for exact reference)
CGS	US Coast and Geodetic Survey, USA
COM	Comitan, México
CON	Concepdión, Chile
CRM	Caravelle, Martinique
C-V	Camacho and Viquez, 1992 (Appendix III)
FDF	Fort de France, Martinique
FELD	Feldman, 1988a,b (Appendix III)
FEM	Feldman, 1988 (Appendix III)
FIE	Gunther Fiedler, Caracas, Venezuela
FIG	Figueroa, 1979 (Appendix II)
FUNV	FUNVISIS, Venezuela
GCG	Guatemala City, Guatemala
GLD	Golden, Colorado, USA
G-M	Güendel and McNally, 1986 (Appendix III)
GUC	Geofisica, Universidad de Chile
GUE	Güendel, 1986 (Apprndix III)
GUTE	Gutenberg and Richter (1954)
IAG	Instituto Astronomico y Geofisico, Univ. de Sao Paulo, Brazil
IBO	Boschini, 1989 (Appendix III)
ISC	International Seismological Centre, UK
ISS	International Seismological Summary, UK

JBS	J.B. Shepherd (usually for macroseismic estimates)
JHO	Johannsen, 1988 (Appendix III)
JIM	Jiménez, (in prep. at time of writing)
J-M	Jordan and Martinez, 1980 (Appendix III)
JSA	Jesuit Seismological Association, St. Louis, USA
KCL	Kire,idjian et al, 1977 (Appendix III)
KRX	Sapper, 1925 (Appendix III)
LAO	Large Aperture Seismic Array, Montana, USA
LARI	Larios, 1979 (see Appendix III for exact reference)
LDE	Morales, 1983 (Appendix III)
LDI	Morales, 1985 (Appendix III)
LDO	Lamont-Doherty Observatory, New York, USA
LEED	Leeds and Moore, 1974 (Appendix III)
LEJ	Leeds, 1974 (Appendix III)
LIM	Lima, Perú
LPA	La Plata, Argentina
LPB	La Paz, Bolivia
LPZ	San Calixto, Bolivia
M-A	Montero and Alvarado, 1988 (Appendix III)
M-G	Montero and González, 1990 (Appendix III)
M-M	McNally and Minster, 1981 (Appendix III)
MAB	Meyer-Abich, 1952 (Appendix III)
MAC	Macroseismic magnitude estimate
MACRO	Macrosesimic epicentre
MAX	González, 1987 (Appendix III)
MCH	Chavez and Castro, 1987 (Appendix II)
MER	Merida, Yucutan, México
MGG	Marie-Galante, Guadeloupe
MON	W. Montero, ECG/UCR (see publication list in Appendix III)
MONT	W. Montero (various publications in Appendix III)
MOS	Moscow, Russia
MPR	Mayaguez, Puerto Rico
MYA	Miyamura, 1980 (Appendix III)
MYS	Miyamura, 1976 (Appendix (III)
NEIC	National Earthquake Information Center, Golden, Colorado, USA
NEIS	National Earthquake Information Service, Golden, Colorado, USA
NSK	Nishenko, 1989 (Appendix III)
OAE	Observatorio Astronomico de Quito, Ecuador
OAX	Oaxaca, México
P-S	Paniagua and Soto, 1986 (Appendix III)
PAL	Palisades, New York, USA
PAS	Pasadena, California
PDE	Preliminary Determination of Epicenter from NEIS/CGS
PEL	Peldehue/Santiago
PRO	Peraldo and Montero (in prep. at time of writing)

PSA	Instituto Nacional de Prevención Sísmica (INPRES), San Juan, Argentina
RESMAC	Red Sísmica Mexicana de Apertura Continental, México
R-I	Father Jesus E. Ramirez, Bogotá, Colombia
ROJ	Rojas, 1993 (Appendix III)
ROR	Russo, Okal and Rowley, 1992
SAA	Shepherd and Aspinall, 1982
SAE	Sykes and Ewing, 1965
SAN	Santiago, Chile
SAT	Shepherd and Tanner, this volume
SBAC	Shepherd et al, 1987
SCB	Observatorio San Calixto, La Paz, Bolivia
SDD	Santo Domingo, Dominican Republic
SJG	San Juan, Puerto Rico
SJP	San Juan, Puerto Rico
SJR	San José, Costa Rica
SIS	Instituto Costarricense de Elctricidad, Costa Rica
SISRA	CERESIS countries of South America
SPEC	Special NEIS solution
SSS	San Salvador, El Salvador
SUAREZ	Gerardo Súarez, UNAM (historical)
SUA	Gerardo Súarez, UNAM (historical)
SUC	Sucre, Bolivia
SUH	Sutch, 1981 (Appendix III)
SYKES	Sykes (L.R.) earthquake catalogue
TAC	Tacubaya, México
TOJ	Toral, 1992 (Appendix III)
TRN	Trinidad
UNM	UNAM, México D.F.
UPA	Universidad de Panamá, Panamá
UPP	Uppsala, Sweden
USCGS	United States Coast and Geodetic Survey
USGS	United States Geological Survey
UVC	Universidad de Valle, Cali, Colombia
V-T	Víquez and Toral, 1987 (Appendix III)
VAO	Valinhos, Brasil
VEG	Vergara, 1990 (Appendix III)
VIQU	Viquez and Camacho, 1993; Viquez and Toral, 1987 (see Appendix III)
W-C	Montero and Climent, 1990 (Appendix III)
W-H	White and Harlow, 1985 (Appendix III)
WCA	Woodward, Clyde Associates
WHE	White, 1988 (Appendix III)
WHT	White, 1985 (Appendix III)
WMP	Montero, 1986 (Appendix III)
WMR	Montero, 1989
ZUN	Ramón Zúniga, UNAM, México, this project

1* Singh and Súarez, 1985 (Appendix II)
2* ISC
3* PDE
4* NOAA
5* Singh and Lermo, 1985 (Appendix II)
6* Singh, Astiz and Havskov, 1981 (Appendix II)
7* Singh, Rodriguez and Espindola, 1984 (Appendix II)
8* Anderson, Singh, Espindola and Yamamoto, 1989 (Appendix II)
9* Molnar and Sykes, 1969 (Appendix II)
10* Same as MCH
11* Same as 7*
12* Nishenko and Singh, 1987 (Appendix II)
13* McNally and Minster, 1981 (Appendix II)