COSTA RICA
COUNTRY FILE

PN-ABG-076
ISN 68153

FINAL REPORT ON THE INSTALLATION OF A PERMANENT NATIONAL SEISMOGRAPHIC NETWORK IN COSTA RICA AND THE ESTABLISHMENT OF AN EARTHQUAKE HAZARDS REDUCTION PROGRAM

May, 1985

PRINCIPAL INVESTIGATORS: Dr. Karen C. McNally
Dr. James B. Gill
Dr. Eli A. Silver
Dr. Jose A. Rial

COSTA RICA COUNTERPART RESEARCHERS: Federico Guendel
Eduardo Malavassi
Rosendo Pujol

Earth Science Board
University of California
Santa Cruz, CA. 95064
(408) 429-4136

GRANT NO. A SB-0000-G-00-4015-00

UNIVERSITY OF CALIFORNIA, SANTA CRUZ

BERKELEY • DAVIS • IRVINE • LOS ANGELES • RIVERSIDE • SAN DIEGO • SAN FRANCISCO SANTA BARBARA • SANTA CRUZ

CHARLES F. RICHTER SEISMOLOGICAL LABORATORY
EARTH SCIENCES

SANTA CRUZ, CALIFORNIA 95064
(408) 429-4137

12 May, 1985

Attn: Mr. Paul Krumpe
Science and Technology Advisor
Office of Foreign Disaster Assistance, Room 1262 A
Agency for International Development
Department of State
Washington, D.C., 20253

Dear Mr. Krumpe:

The following Final Report on the Installation of a Permanent National Seismographic Network in Costa Rica and the Establishment of an Earthquake Hazards Reduction Program is submitted to USAID by the University of California, Santa Cruz, for review of Project accomplishments through 1984.

Following item C2 of Attachment 2 (Program Description) to Mr. L. E. Stanfield's letter of January, 1984, we are sending USAID 30 English language copies of our final report. According to the same memorandum we understand that USAID may distribute copies for spanish translation by Costa Ricans, as appropiate.

If you have any questions regarding the enclosed report, please do not hesitate to contact me for more information.

Sincerely yours,

Karen C. McNally

Dr. Karen C. McNally
Principal Investigator

TABLE OF CONTENTS

LETTER OF TRANSMITTAL ii

TABLE OF CONTENTS..... iii

LIST OF REPORT FIGURES..... v

LIST OF TABLES..... vi

LIST OF FIGURES IN APPENDICES..... vi

EXECUTIVE SUMMARY..... vii

Section

I. INTRODUCTION..... 1

Background..... 1
Earthquake Susceptibility in Costa Rica..... 2
Project Highlights..... 3

II. PROJECT GOALS AND ACCOMPLISHMENTS..... 7

Summary of Project Efforts Through 1984..... 8

Effort 1: Establish National Seismograph Network..... 8
Effort 2: Scientific Expertise, Cooperative Projects, and Data Analysis.....12
Effort 3: Earthquake Preparedness.....15
Effort 4: Energy Development and Mineral Exploration.....17
Effort 5: Traineeships and Scholarships.....21

III. PROJECT ANALYSES 24

Geology.....24

Geological Reconnaissance.....24
Geologic Fault Assessment.....25
Coastal Ranges.....25
Talamanca Range.....26
Summary.....27

Volcanology.....29

Geophysical Monitoring.....29
Surveying.....30
Seismicity.....30

Tilt.....31
Temperature and Chemistry.....31
Geologic Risk Assessment.....32
Summary.....36

Synthetic Accelerograms.....37

Computer Modelling.....37
Crustal Model.....38
Strong Motion Waves.....38
Earthquake Mechanisms.....39
Examples.....39
Accelerogram Analysis.....42
Summary.....43

Seismology.....45

Earthquake Potential Analysis.....45
Earthquake Damage and Intensity.....58
Earthquake Seismicity and Tectonics.....60
Summary.....67

IV. CONCLUSIONS.....70

V. FOOTNOTES.....74

VI. PROJECT RELATED PUBLICATIONS, REPORTS, AND ABSTRACTS..78

VII. AGENCIES AND INDIVIDUALS CONTACTED.....81

APPENDICES.....83

Appendix A: Equipment Purchased and Shipped to Costa Rica.....84
Appendix B: Costa Rica Personnel.....87
Appendix C: Technical Description of Seismographic Network Operation in Costa Rica.....89
Appendix D: Technical and Emergency Communication Relationship.....94
Appendix E: U.S. Personnel Travel Log.....97
Appendix F: Technical Analysis of Volcan Arenal.....98
Appendix G: Volcan Turrialba Stratigraphy.....99
Appendix H: Earthquake Intensity Maps.....103
Appendix I: Modified Mercalli Scale.....107
Appendix J: Synthetic Waveform Models.....110

LIST OF REPORT FIGURES

FIGURES PAGE

1: Seismographic and Strong Motion Stations Installed through 1984 4
2: Photographs of Newly Completed Seismology and Volcanology Laboratory in Costa Rica 10
3: Probability Increase of Damaging Earthquake in the Central Valley region of Costa Rica 14
4: Geology of Costa Rica 25
5: Faulting Structure in Costa Rica..... 26
6: Location of Volcanoes in Costa Rica 29
7: Topography of Volcan Turrialba 33
8: Physiography of the Summit of Volcan Turrialba 35
9: Accelerogram of a Subduction Earthquake..... 40
10: Accelerogram of a Subduction Earthquake..... 40
11: Accelerogram of a Subduction Earthquake..... 41
12: Accelerogram of a Strike Slip Earthquake..... 41
13: Accelerogram of a Strike Slip Earthquake..... 42
14: Inferred Surface Faults in the Vicinity of the Central Valley 46
15: Earthquakes Damaging to the Central Valley, Costa Rica 47
16: Rupture Zones and Epicenter of Large Shallow Earthquakes in Costa Rica 48
17: Topographic Relief of the Cocos Ridge 49
18: Time-Space Projection of Costa Rica Earthquakes, 1900-1983, $M_s > 7.0$ 51
19: Earthquake Magnitude as a Function of Time 52
20: Correspondence of Volcanic Eruptions and Earthquake Activity in Costa Rica 56
21: Intensity and Aftershock Area of Historic Earthquakes in Costa Rica..... 59
22: Intensity Estimates of Future Earthquakes in Costa Rica 59
23: Five Large Earthquake Events Since 1974..... 61
24: Three Major Subduction Events Since 1974..... 63
25: Regional Tectonic Framework..... 64
26: Earthquakes in Costa Rica, April-December, 1984 65
27: Cross Section of Earthquakes in Costa Rica, April-December, 1984, Showing Subduction..... 66

LIST OF TABLES

TABLES PAGE

1: Geographic Coordinates of Installed Seismic and Strong Motion Stations..... 6
2: Silicon dioxide (SiO_2) Content of Common Volcanic Rocks..... 34
3: Seismicity of Costa Rica, 1898-1983, $M_s > 7.0$ .. 51

LIST OF FIGURES IN THE APPENDICES

FIGURES PAGE

28: Typical Relationship Between Technical and Emergency Response..... 95
29: Types of communication with the Civil Defense Office and the Press..... 96
30: Summit Geology of Volcan Turrialba.....100
31: Stratigraphy of Turrialba Crater.....100
32: Intensity Map of 2 September, 1841 Earthquake ..103
33: Intensity Map of 28 March, 1851 and 30 December, 1888 Earthquakes 104
34: Intensity Map of 13 April, 1910 Earthquake 105
35: Intensity Map of 4 May, 1910 Earthquake 106
36: Synthetic Waveform.....110
37: Synthetic Waveform.....111
38: Synthetic Waveform.....112
39: Synthetic Waveform.....113
40: Synthetic Waveform.....114

EXECUTIVE SUMMARY

The primary objective of the joint University of California Santa Cruz (UCSC), USAID, and Costa Rica Project was the establishment of a permanent national seismograph network in Costa Rica. UCSC's two year participation in this effort led to the initialization of five major efforts which have either been completed or are currently being managed by Costa Rican Agencies.

These five efforts included equipment purchase, staff training in equipment operation and maintenance, research in the fields of geology, volcanology, and seismology, the development of multi-agency participation and specialized training in related fields.

The Project has been succesfully launched with major equipment purchases being completed between 1982 and 1984. Installation of over half the equipment necessary to the seismograph network has been completed. Training has been provided to appropriate individuals so that the remaining equipment can be installed and maintained without UCSC's direct involvement.

Research findings by Project Staff, are presented in the body of this report and summarized very briefly below. Training in data collection and reduction methodologies and data analysis have been provided to a number of individuals, both in Costa Rica and the United States. This process has facilitated the establishment of Costa Rican researchers and technicians to continually maintain the network and update the findings prepared and presented in the following pages.

Major research accomplishments and findings include the following points:

- A number of potential hazards to the major population centers of Costa Rica have been identified.
- Two main active surface fault systems, one in the Talamanca Range and the other in the Coastal Range were identified through geological reconnainscence.
- New tools for the study of small faulting systems should continue to be developed.

- Four volcanoes are now routinely monitored. Poas and Irazu were identified as the quietest of these four, with Turrialba and Arenal following respectively.

- Turrialba has an explosivity potential similar to that of Irazu in 1964, though the potential for a debris avalanche still exists.

- Arenal is unlikely to approach the explosivity it had in 1968 as its magmas are being effectively degassed.

- Theoretical synthetic accelerograms have been developed using computer programs to model groundshaking intensities.

- There is a good probability of an earthquake event from shallow surface faulting in central Costa Rica during the coming years.

- Earthquake preparedness planning should include measures for two potential earthquakes: (1) a moderate sized, but highly damaging earthquake in the Central Valley Region and (2) a large ($M_s \geq 7.5$) earthquake along the subduction zone (that might cause serious damage, though be less disruptive to the San Jose/Cartago area than a Central Valley earthquake.

- Subduction beneath the central region in Costa Rica may be aseismic; alternatively this may be the site of a seismic gap for earthquakes with long repeat times.

- Subduction of the Middle America Trench, off Costa Rica continues all the way to the abutment of the Panama Fracture zone off the southeastern portion of the country.

- The Cocos Ridge, an aseismically produced ridge, is subducting under the Caribbean Plate seismically.

I. INTRODUCTION

Background

The following report, prepared by the University of California, Santa Cruz (UCSC), summarizes the second year work efforts of a proposed five year project on the Installation of a Permanent National Seismographic Network in Costa Rica. It additionally discusses progress toward the establishment of an Earthquake Hazards Reduction Program in Costa Rica. This final report has been prepared and presented to the United States Agency for International Development (USAID), at the request of USAID.

Costa Rica, historically susceptible to highly damaging earthquakes, anticipates that the results of this five year Project will limit impacts resulting from seismic and volcanic eruptions through the installation of equipment that provides an early warning system of such events. The operations of this Project should also provide assistance toward a speedy recovery from the occurrence of any damage caused by an earthquake or volcano by emphasizing the preparation of the public, government agencies, and institutions in providing relief. The most immediate result of the dual objectives of this Project, initiated by the University of California, Santa Cruz, will be a reduction of human mortality and prevention of major damages to newly built structures.

Secondary benefits will be derived from the research aspect of this Project as well. As historical records are compiled and updated with currently collected data, their analysis will provide Costa Rica with a firm base from which to predict future events. This will enable appropriate planning to occur with regard to the location, size, and types of development throughout the country, especially the populated areas. In addition to reducing economic expenditures by changes in building requirements, the development of a comprehensive data base will provide an important source of information for mineral exploration, water supply and power line location.

Instrumentation is needed to monitor seismic activity to keep USAID, the Government of Costa Rica (GOCR), and Project Staff alert to potentially damaging events and able to prepare for emergency relief. Technical training of Costa Ricans to develop monitoring systems and prepare against such natural disaster is planned with U.S. technical assistance.

Earthquake Susceptibility in Costa Rica

Destructive earthquakes have occurred throughout the history of Costa Rica and will occur again in the future. The old city of Cartago, located near the Country's present capital of San Jose, has repeatedly suffered severe damage due to earthquakes. Today, Costa Rica faces a critical earthquake threat with the very real possibility of substantial losses in life, detriment to the economy, and damages to the social infrastructure, particularly in San Jose, the center of Costa Rican activity.

Costa Rica is highly susceptible to severely damaging earthquakes similar to those which have occurred in Managua, Nicaragua, and in Guatemala. The two types of earthquakes most likely to be experienced in Costa Rica are:

1) A relatively small (M_s = 5.0-6.5), though very shallow and highly damaging earthquake, in the vicinity of the capital city of San Jose or the metropolitan areas of Cartago and Alajuela.

2) A large ($M_s \geq 7.5$) subduction zone earthquake along the Pacific Coast of Costa Rica.[1]

A relatively small earthquake, as described in 1 above, occurred in 1910 and destroyed Cartago. The data indicate that prior to 1910 similar earthquakes have occurred in this region about every 37 years since 1638. The data currently available also indicate a very high probability of this type of event reoccurring in the future. More specifically, one chance in three over the next three years, with the likelihood of such an event increasing with time thereafter.

For comparison, the likelihood of this type of earthquake is about nine times as great as that for a major earthquake in southern California along the San Andreas fault. Special efforts in earthquake preparedness planning, similar to efforts in Japan, are under way in Southern California. As in Japan and California, hundreds to thousands of lives in Costa Rica could be saved by the work of the Costa Rica-University of California Project funded by the Office of Foreign Disaster Assistance (OFDA).

The new data from the United States Agency for International Development (USAID) seismographic network in Costa Rica reinforces our earliest interpretation (previously based on only the scanty data from the world wide network) that the second type of event, a large earthquake ($M_s \geq 7.5$) should be expected and may occur along the northern coast near the border with Nicaragua.

The Costa Rica-University of California Project represents an accelerated work effort for earthquake hazard reduction, earthquake preparedness planning, and the gathering of necessary data with monitoring installations (i.e., the seismographic network, volcano monitoring, and strong ground motion networks) as well as training for a highly organized technical staff of Costa Ricans. These endeavors motivated a sustained effort on the part of the Government of Costa Rica (GOCR) to organize and reduce the country's vulnerability, particularly through ongoing practice drills to be initiated by technical laboratories.

Project Highlights

The Project staff's initial efforts have concentrated on the region near the capital, San Jose, due to its dense population and locus as the country's center of government. With the instrumentation being installed in the northern and southern sections of Costa Rica, technicians will be able to provide detailed detection maps of activity and preparedness planning information for Costa Rica during the next year. The instruments obtained and installed to date are indicated in Figure 1. 1985 marks the final major equipment purchases and installation. (See Appendix A for complete list of purchases.)

Below are some highlights of Project accomplishments to date; a more complete work summary is provided in the following pages of this report.

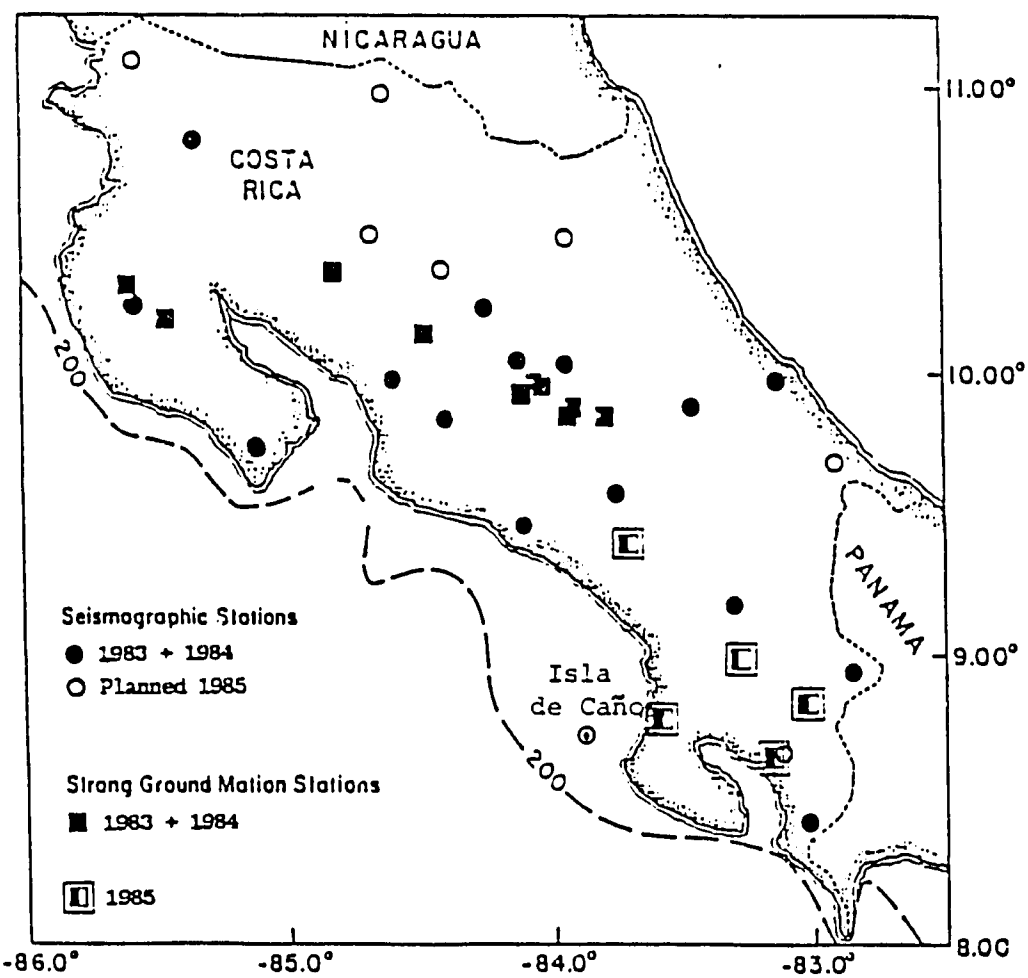
- A seismological laboratory has been constructed and is currently in operation and new equipment is continually being added.
- New incoming data are being processed.
- Since April, 1984, monthly bulletins have been regularly produced and distributed throughout Costa Rica and the world.

- Seven seismograph stations were procured in 1984 and added to the eight seismograph stations which were bought in 1983, bringing the total stations purchased for the two years to fifteen.

- To date, eleven of the fifteen seismograph stations have been installed and are operational, (see Table 1).

FIGURE 1

SEISMOGRAPH AND STRONG MOTION STATIONS INSTALLED THROUGH 1984



- Ten strong motion stations were purchased in 1984, and added to the same number of stations that were bought in 1983, bringing the total number of strong motion stations procured for the two years to total of twenty stations.

- To date, ten of the twenty strong motion stations have been installed and are operational, (see Table 1), with another five due to be installed soon.

- Special analyses of incoming data, development of local scientific expertise, and training in the use of a new emergency computer are now under way. Training is done both in Costa Rica and through working trips for Costa Ricans to U.S. centers.

- Routine earthquake reporting procedures have been established. A new center for an earthquake education program and volunteer network is in the process of being organized with the Extension Program of UNA, and with guidance from the Civil Defense Office.

- An organized emergency response plan for the technical laboratories is being developed in coordination with the Civil Defense Commissioner, Lenin Saenz.

- New results from studies for volcano hazards indicate that Turrialba exploded 2,300 years ago, depositing scores of meters of debris on the crater rim to the west and 10 meters on the crater rim to the east, 10-15 km in the direction of the population of Cartago. The character and distribution of the products of subsequent eruptions have been determined, providing the basis for planning about future eruptions.

- New geochemical data have been analyzed and are being consolidated for use in volcano monitoring and eruption warning.

- Previous monitoring a of Costa Rica have been expanded by using new techniques (electronic tiltmeters) and purchasing of lab and surveying equipment to create and standardize a national volcano monitoring system.

TABLE 1

PRELIMINARY GEOGRAPHIC COORDINATES OF INSTALLED SEISMIC AND STRONG MOTION STATIONS

Seismic Station		Longitude		Latitude		Elevation[1]
(IRZ)	Irazu	83°	51.943'	9°	58.465'	3380
(POA)	Poas	84°	13.024'	10°	09.140'	2093
(QPS)	Quepos	84°	07.935'	9°	24.186'	83
(CDM)	C. De la Muerte	83°	45.945'	9°	33.310'	3470
(EPA)	Esparza	84°	35.788'	9°	59.261'	310
(PTCR)	Puriscal	84°	25.569'	9°	47.370'	1510
(TUI)	Tuis	83°	33.440'	9°	50.505'	1300
(HDC)	Heredia (Z,2H)	84°	07.000'	10°	01.425'	1220
(CAO)	Cobano	85°	06.200	9°	42.070	263
(JUD)	Juan Dias	85°	32.825	10°	09.720	844
(RIN)	Rincon de la Vieja	85°	21.500	10°	46.415	755

Strong Motion Station	Longitude		Latitude	
Cartago Central	83°	56.5	9°	51.7
Instituto Technologico	83°	51.5	9°	51.3
UCR	84°	03.0	9°	56.4
Hatillo	84°	05.0	9°	55.0
Cachi	83°	47.1	9°	50.6
San Ramon	84°	28.4	10°	05.2
Santa Cruz (Guanacaste)				
Nicoya				
INS Bldg. (San Jose)				
Tilaran				

[1] Elevation in meters

II. PROJECT GOALS AND ACCOMPLISHMENTS

To complete the objectives of this Project there are five major, simultaneous efforts geared to maintain an accelerated work schedule.[2] These five concurrent efforts are:

EFFORT 1: Establish a permanent national seismograph network in Costa Rica and train local personnel in the operation and maintenance procedures of this network.

EFFORT 2: Continue to develop scientific expertise in Costa Rica and establish cooperative projects to process and analyze the incoming data.

EFFORT 3: Initiate an earthquake preparedness project and develop earthquake response planning with the Government of Costa Rica.

EFFORT 4: Provide technical assistance in energy development, mineral exploration, and hazard reduction analysis, and work to reduce insurance problems in Costa Rica for immediate economic applications.

EFFORT 5: Provide short-term traineeships and scholarships (in the United States) for advanced technical training, in economically related fields, for Costa Rican individuals.

These five efforts support the USAID statement in October, 1982 of the Project's principal objectives as:

"... the installation of a Permanent National Seismograph Network (RSN) in Costa Rica and to establish a hazards reduction program in cooperation with the Government of Costa Rica."[3] (See Appendix B for a list of Costa Rican Personnel.)

This same report further indicated that the seismological data that would be made available by this Project should be used:

- for disaster preparedness planning in Costa Rica;
- for the evaluation of seismic risk in Costa Rica;
- to provide information which can be used to suggest improvements to the Seismic Building Code for Costa Rica;
- for engineering design of important structures such as hydroelectric projects, bridges, communication centers, hospitals, etc.;
- for tectonic and geological interpretations and geothermal development,
- for volcanic hazards assessment and monitoring; and
- for fundamental studies in seismology, tectonics, and volcanism.

Summary Of Project Efforts Through October, 1984

The following section is a summary of project accomplishments through 1984. Each of the five efforts described above is presented here with goals designed to help attain the Project objectives and steps that have been accomplished to reach those goals.

EFFORT 1: ESTABLISH A NATIONAL SEISMOGRAPH NETWORK IN COSTA RICA AND TRAIN LOCAL PERSONNEL IN THE OPERATION AND MAINTENANCE PROCEDURES OF THIS NETWORK.

GOAL: **Obtain and install eight seismograph stations to expand and upgrade existing network of seven stations to fifteen stations.**

ACCOMPLISHMENTS:

- Eight seismograph stations have been installed in central Costa Rica, (because of population concentrations), with two stations located near volcanoes in order to monitor both tectonic and volcanic seismicity.

- Of the seven additional stations that have been purchased, three have been installed in other sections of the country, and the remainder are being prepared for installation.

- The network has been designed to maintain operation during disasters through radiotelemetry, with optional alternative transmission routings. (See Appendix C.)

- Small computers for emergency operations have been selected, purchased, and are being programmed by UCSC for Costa Ricans, for the specific needs of this Project.

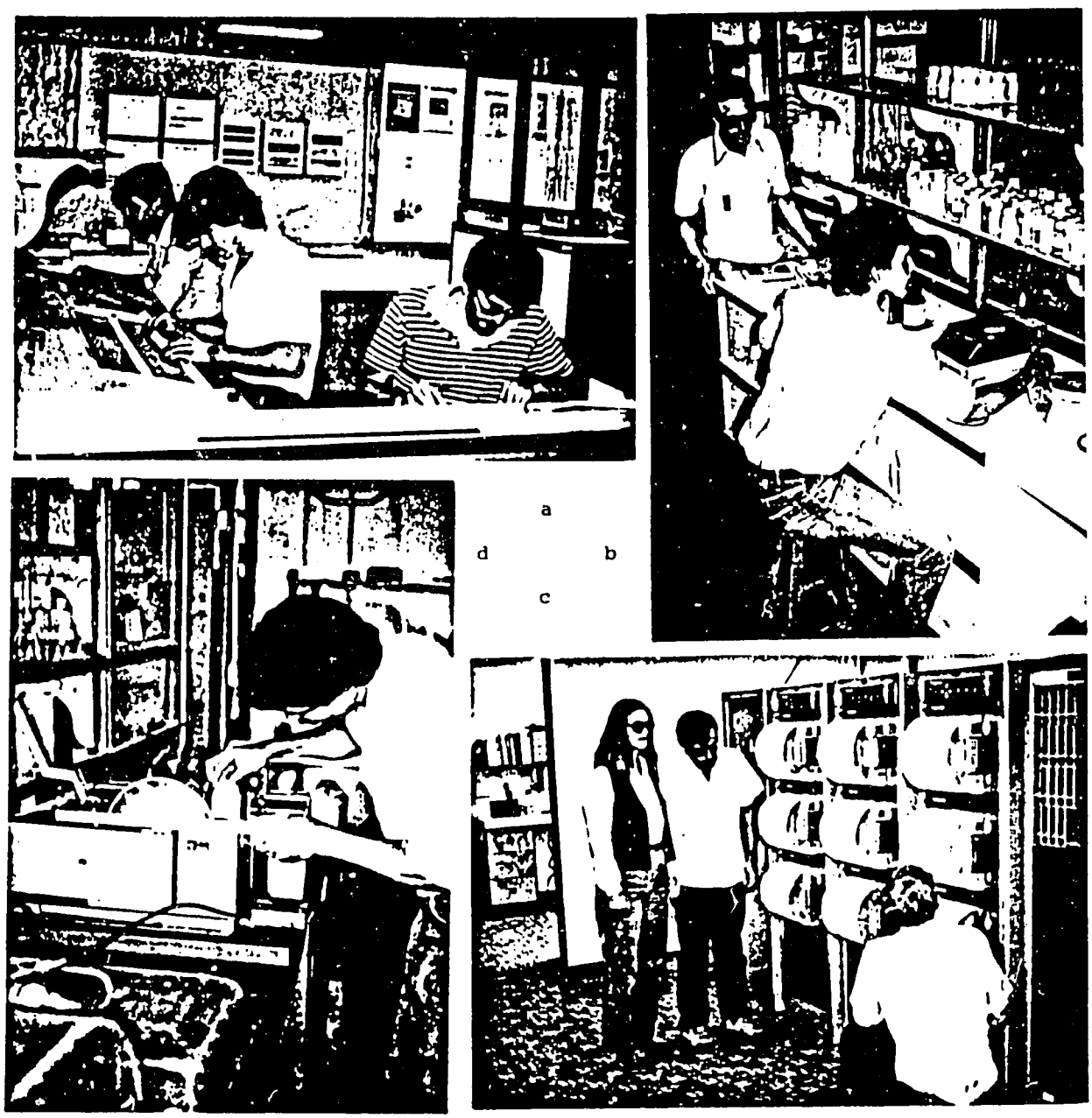
- A standby power generator has been purchased for use during emergencies and power outages.

- Four portable seismograph units have been purchased and are now in Costa Rica. With three existing units already in use in Costa Rica, the portable network now totals seven stations. (The portables will supplement the permanent stations during earthquake and volcano emergencies.)

- The new earthquake laboratory and test facility has been constructed, is currently in operation, and new equipment is still being added. (See Figure 2.)

FIGURE 2

PHOTOGRAPHS OF NEWLY COMPLETED SEISMOLOGY AND VOLCANOLOGY LABORATORY IN COSTA RICA



a. Seismology Measuring Room

b. Geochemistry Lab

c. Earthquake Data Recording Room

d. Thin Section Lab

GOAL: **Obtain and install ten strong motion accelerographs to expand and upgrade the existing network to twenty sites.**

ACCOMPLISHMENTS:

- Strong motion equipment location sites were selected to optimize coverage for engineering applications based on earthquake activity, population centers, and critical structures in Costa Rica.
- The first ten strong motion accelerographs have been installed.
- After equipment was installed in Costa Rica, a final checkout was done by University of California, Santa Cruz personnel in conjunction with Costa Ricans.
- Ten stations for the second phase of installation have been purchased and shipped to Costa Rica.
- All stations have been checked and calibrated by UCSC personnel and Costa Rican trainees, with assistance from the Division of Mines and Geology, State of California, to guarantee correct performance.(4)

GOAL: **Purchase age dating laboratory equipment for volcanic risk analysis.**

ACCOMPLISHMENTS:

- Four Tennelec TC256 alpha spectrometers, one 2000-channel analyzer and a supporting microcomputer have been purchased, installed, and are operational.
- Age dating laboratory equipment will be used to determine the age of volcanic rocks.

EFFORT 2: CONTINUE TO DEVELOP SCIENTIFIC EXPERTISE IN COSTA RICA AND ESTABLISH COOPERATIVE PROJECTS TO PROCESS AND ANALYZE THE INCOMING DATA.

GOAL: **Train Costa Rican personnel to operate and maintain the network of seismic instruments.**

ACCOMPLISHMENTS:

- On-the-job training in network installation and maintenance, trouble shooting techniques, and equipment testing and checking procedures have been provided for personnel in Costa Rica by Mr. John Lower (a senior U.S. engineer).
- Direct technical training is being provided to six Costa Ricans in electronics, computer programming and data analysis.

GOAL: **Continue development of a data reduction program to calculate earthquake locations and publish catalogs of this data.**

ACCOMPLISHMENTS:

- Data reduction routines to compile and publish catalogs of basic earthquake location data have been established in Costa Rica.
- The first compiled earthquake catalogs have been distributed monthly since 1 April, 1984.
- Communications regarding earthquakes and volcanoes are being provided on a regular basis to the Government of Costa Rica Civil Defense authorities.
- Twenty-four hour emergency monitoring procedures are being established.

GOAL: **Systematically develop a more fundamental knowledge of earthquakes in Costa Rica and their relation to geological features in order to locate regions of potential hazards.**

ACCOMPLISHMENTS:

- The relation of earthquakes and geologic features in Costa Rica are being evaluated from the new data provided by the seismograph network. (See Project Analysis section cf this report.)

GOAL: **Analyze the seismic history of Costa Rica in order to identify sources of earthquakes which present hazards to the Country.**

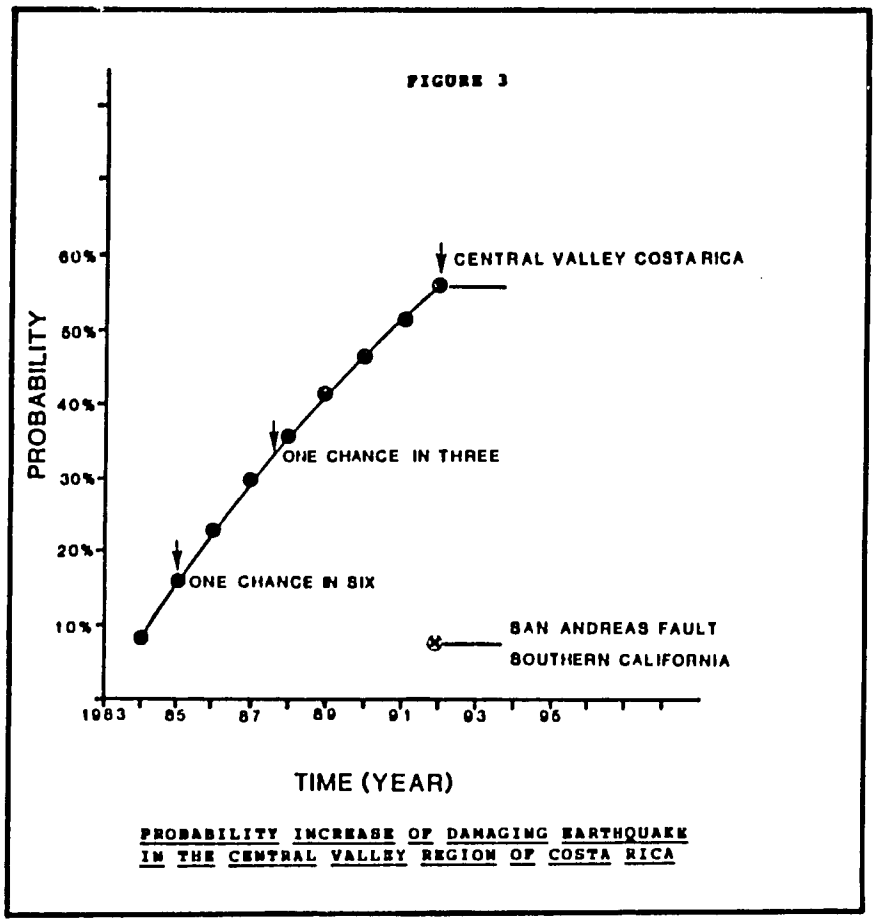
ACCOMPLISHMENTS:

- Large earthquakes along the Pacific subduction zone have been analyzed with seismogram modeling techniques.

- Results to date indicate faulting mechanisms similar to those found in Mexico, rather than El Salvador, as previously assumed.

- The earthquake history and future earthquake potential are being carefully evaluated; current results have been presented and reviewed by USAID, USGS, and the Costa Rican government.

- The probability increase for damaging earthquakes in the Central Valley, Costa Rica (Cartago-San Jose area) with increasing time have been assessed. (See Figure 3.)



GOAL: **Determine the nature of earthquake strong ground motion and local building response characteristics as records become available from moderate earthquakes.**

ACCOMPLISHMENTS:

- In preparation for larger earthquakes and forthcoming data from the strong motion instruments, theoretical calculations of ground shaking intensities for earthquake response planning have been conducted.

- Development of damage scenario maps for emergency planning by the Civil Defense Office of the Costa Rican government has begun.

- A typical plan for technical communication during an emergency has been prepared by Dr. McNally, at the request of the Costa Rican government.[5] (See Appendix D.)

- Emergency radio communications between the technical laboratories and the Civil Defense Office have been discussed with Mr. Paul Bell.

EFFORT 3: INITIATE AN EARTHQUAKE PREPAREDNESS PROJECT AND DEVELOP EARTHQUAKE RESPONSE PLANNING WITH THE GOVERNMENT OF COSTA RICA.

GOAL: **Assist Costa Rica in earthquake planning at the neighborhood, working center, and elementary and high school levels, emphasizing the self-help aspects of earthquake planning.**[6]

ACCOMPLISHMENTS:

- Project plans and schedules have been designed and Project staff have been identified at the Extension Branch of the National University.

- Project design is for coverage of central Costa Rica, (where more than half of the population of the country lives), with public education centers (which provide a very large and receptive audience), playing a very important role.

- A network of volunteer instructors, (science teachers and other community leaders with a background knowledge in science), will be organized to provide talks to different groups in 1985.

- More than a hundred talks were given by Costa Ricans in 1983 and 1984 to very different community groups, including, medical doctors at the Children's Hospital and community groups at the neighborhood level.

- A network of volunteer observers will be created nationwide to gather information about earthquake effects and to improve interaction between scientists and the community for further self-help, community level earthquake planning.

GOAL: **Assist Costa Rican's in developing the following working plan for 1985:**

a. Selection of educational materials by Costa Rican Project staff members.

b. Translation (if necessary), adaptation, and printing of educational aids for Project use in Costa Rica.

c. Community leader identification and selection.

d. Workshop to prepare community leaders on technical aspects related to the Project and the use of educational aids.

e. Talks by community leaders in central Costa Rica with close advice and support from Project staff members.

EFFORT 4: PROVIDE TECHNICAL ASSISTANCE IN ENERGY DEVELOPMENT, MINERAL EXPLORATION, AND HAZARD REDUCTION ANALYSIS, AND WORK TO REDUCE INSURANCE PROBLEMS IN COSTA RICA FOR IMMEDIATE ECONOMIC APPLICATIONS. (See Appendix E for a log of travel by U.S. Personnel in Costa Rica.)

GOAL: **Provide tectonic maps, assistance and technical expertise to Costa Rican government agencies for:**

1) Oil exploration, (RECOPE);
2) mineral exploration (Division of Mines and Geology);
3) analysis of vulnerability of lifelines (water, power, transportation); and
4) seismic and volcanic risk analysis.

ACCOMPLISHMENTS:

- **Oil and Mineral Exploration:**
  - RECOPE has confirmed To Dr. McNally, the assistance this project has provided them with oil exploration.
  - Dr. Silver, a UCSC professor of Earth Science, gave a seminar in Costa Rica on the geology of the country which assisted RECOPE personnel with an understanding of the location and potential for oil.
  - Dr. Silver's offshore research, using depth charges, will also provide RECOPE with new data that will continue to assist them in oil exploration.
  - Federico Guendel's research findings on plate subduction, based on synthetic waveform modelling, provides information of the earth's movements, from which deductions in the location of minerals, particularly copper may be made.

- The information generated by this project is available to any organization or agency which seeks the findings developed at UCSC.

  - Routine communications are being developed with RECOPE and other government agencies in Costa Rica to guarantee information distribution and exchange of data with potential information users.

- **Geological Fault Hazard Component:**

  - Two seismically active zones in the Central Valley were surveyed for geologic and geophysical evidence of the location of active faults.

  - A reconnaissance of the geology of the Coastal Range was undertaken to determine the timing and style of deformation of the forearc region in southwest Costa Rica and its relation to the gross tectonic setting in the region.

- **Volcanic Hazard Component:**

  Geophysical & Geochemical Monitoring:

  - Four volcanoes (Irazu, Turrialba, Poas, and Arenal) are now routinely monitored by several techniques, including, surveying, seismicity, tilt, and the measurement of the temperature and chemistry of gases and erupted materials.

  - Monitoring is gradually being developed for Volcan Rincon de la Viejo in the northern part of the Country.

- To improve monitoring capability, seismometers were installed on two volcanoes, dry tilt networks completed at four, and electronic tilt-meters purchased for the same four (two of them, installed at Arenal and Irazu, are being experimentally tested).

- Dry tilt arrays have been installed on all four volcanoes and are resurveyed quarterly.

- Baseline data are being evaluated both in Costa Rica and at UCSC to determine what changes in seismicity and tilt can be used to predict eruptions.

- Twenty samples erupted from Arenal between 1968 and 1984 were analyzed for the concentration of 23 elements.

Geologic Risk Assessment:

VOLCAN TURRIALBA

- Volcan Turrialba was selected by Costa Rican and UCSC personnel to be the pilot Project for volcanic hazard assessment with emphasis placed on mapping of hazardous deposits and determining their character and age.

- Two months of fieldwork on the Volcan Turrialba resulted in detailed understanding of its most recent history which included at least one very large, previously unrecognized event.

- The aerial extent of airfall from the 1863-65 eruption and its three predecessors has been mapped and samples collected.

- Five samples from Volcan Turrialba and Arenal have been radiocarbon dated with the earliest sample being 8250 b.p.

GENERAL

- A lab for microscope study of volcanic rocks in thin sections has been created at UNA.

- A rock saw for thin section preparation has been customized at UCSC and shipped to Costa Rica.

- A state-of-the-art lab for radiometric dating of very young volcanic rocks by analysis of Uranium disequilibrium decay products has been nearly completed at UCSC for analysis of Costa Rican samples.

- Two tiltmeters for each of the four monitored volcanoes have been purchased and, though, only two have been experimentally installed to date, all tiltmeters are planned for installation. (7)

GOAL: **Prepare seismic zoning maps for the National Insurance Company (INS) and help develop a more rational insurance policy, in order to reduce Costa Rican expenditures for reinsurance from foreign companies, for land use planning and seismic risk analysis.**

ACCOMPLISHMENTS:

- Seismicity maps, being completed as the new data accumulate, are to be used for seismic zoning analysis based on seismic risk for land use and other planning applications.

- Information regarding seismicity of Costa Rica is being provided on a regular basis to the National Insurance Company.

EFFORT 5: PROVIDE SHORT-TERM TRAINEESHIPS AND SCHOLARSHIPS (IN THE UNITED STATES) FOR ADVANCED TECHNICAL TRAINING, IN ECONOMICALLY RELATED FIELDS, FOR COSTA RICAN INDIVIDUALS.

GOAL: **Provide travel expenses to Costa Ricans for short-term traineeships at technical conferences.**

ACCOMPLISHMENTS:

- Eduardo Malavassi, representing the Latin American countries, attended workshops and conferences in Hawaii, covering discussions for international cooperation and assistance in case of volcanic crisis, as well as on-the-job-training for many volcanologists around the world.(8)

- Eduardo Malavassi visited UCSC and the USGS-operated Cascades Volcano Observatory (CVO) and the Hawaii Volcano Observatory (HVO) to learn about state-of-the-art procedures to install and operate electronic tiltmeters, resulting in correct installation of tiltmeters in Costa Rican volcanoes

- Participation with the field crews in regular monitoring activities, both at CVO and HVO, provided valuable information and perspectives about the latest advancements on volcano monitoring, as well as an exchange of information and computer programs with staff members there.

- Rodolfo Van der Laat, from UNA, attended a Unesco sponsored workshop for volcano observatory personnel from countries in the Southwest Pacific and a Natural Hazards Seminar held in the Philippines, Nov 13 - Dec 13, 1984. Mr. Van der Laat also travelled to the Hawaii Volcano Observatory to discuss current observational techniques and methods.

- Dr. T. Shakal (head of the Strong Motion Instrumentation Program) and UCSC, set up and presented a short training program for two electronic technicians from Costa Rica for two weeks during July 16-27, 1984, at the California Division of Mines and Geology in Sacramento, California.

- Maria LaPorte and Jorge Gutierrez attended the Eighth World Conference on Seismic Engineering in San Francisco from July 21-28, 1983.

- Costa Rican technicians visited the Charles Richter Seismological Laboratory and became acquainted with seismic equipment for later use in Costa Rica.

- Short training for a computer technician in the use of the DEC-350 computer, software implementation and computer-to-computer communication for data processing is being planned at the Charles Richter Seismological Laboratory.

- Educational aids will be reviewed and selected, as needed, from the Southern California Earthquake Preparedness project by two Costa Rican staff members for the disaster and earthquake planning component of the Project.

- Marino Protti, a UNA staff member, attended the Geophysical Workshop (sponsored by Pan American Institute of Geography and History-Organization of American States) for Central America and the Caribbean countries held in Panama, to discuss coordination and new advancements at the regional level.

GOAL: **Research assistantships (scholarships) for advanced technical training (Ph.D) for Costa Ricans in the United States (at University of California; Earth Science and Engineering Departments), in economically related fields.**

ACCOMPLISHMENTS:

- Federico Guendel is currently working to complete a Ph.D. program in Seismology, through the Charles F. Richter laboratory at UCSC.

- Eduardo Malivassi began work in January, 1985, toward a Ph.D. program in volcanology at UCSC.

III. PROJECT ANALYSES

Four separate analyses are presented in this section of the report which cover geology, volcanology, strong motion synthetic accelerograms, and seismology. Each section covers a major task of the Project for installation of a seismographic network and establishment of an earthquake hazard reduction program.

GEOLOGY

The major systems of potentially active surface faults in Costa Rica can be divided into three tectonic and geographic entities. Two of the three major geographic systems of potentially active surface faults in Costa Rica, the Coastal Range and Talamanca Range are discussed below. (See Figure 4.) A third region of potentially active faulting lies in the eastern part of the country, in the vicinity of Limon. It is a complex fold and thrust belt that is cut by high angle faults. This system continues offshore to the east to form the Northeast Panama thrust belt. There has been no fieldwork with this fault system, but there are scientist at RECOPE, that Project staff have communicated, who have significant information on these structures.(9)

Geological studies for this project focused on two aspects: 1) The nature and timing of faulting in the southern coastal ranges, and 2) the nature of faulting in the Talamanca range, in the vicinity of Cartago. Provided here is a synopsis of the significant results and their bearing on a program for hazard reduction in Costa Rica.(10)

A. Geological Reconnaissance

Several approaches were used to study the Coastal and Talamanca Range areas and associated faulting patterns. The first was to construct a country-wide fault map based on existing maps and aerial photographs. The second was to do geological field work in selected areas, to check the nature and timing of faulting, and the veracity of our initial map. The third approach was to carry out a series of gravity transects across faults thought to be especially significant in the densely populated San Jose area.

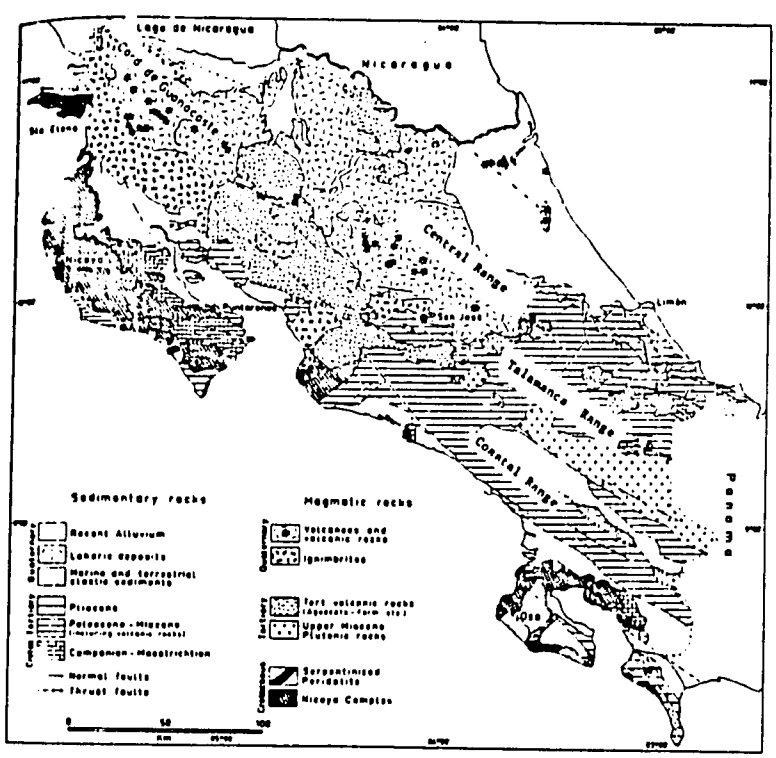
B. Geologic Fault Assessment

1) Coastal Ranges

The westernmost potentially active surface faults in Costa Rica comprise those of the coastal ranges. (See Figure 4.) They have been mapped as dominantly thrust or reverse faults with a northwest trend that parallels the ranges. Our field mapping supported this view and showed that the faults are largely steeply dipping to the northeast. Some of these faults can be seen to cut igneous dikes that were dated at 13.2 million years. The faults must have been active after this time, but we have no stratigraphic indicator to restrict the final timing of activity on them. Earlier work by Woodward-Clyde consultants demonstrated that some of these faults have been active during the past 10,000 years, and so must be considered potentially active.[11] Very high rates of uplift have been measured along the range front, and the present depositional surface can be seen to tilt eastward toward the Talamanca range.

FIGURE 4

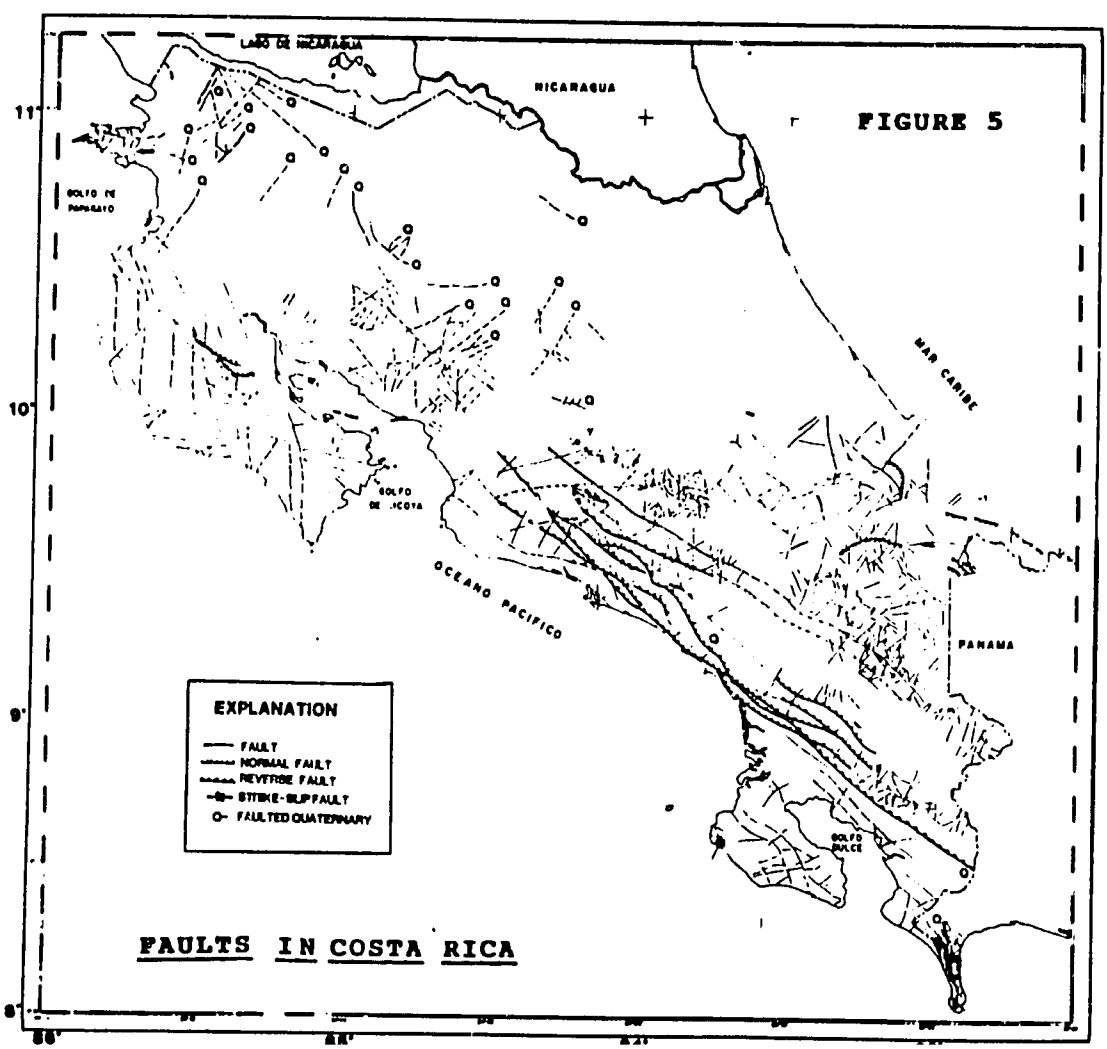
GEOLOGY OF COSTA RICA



2) Talamanca Range

The second group of faults in Costa Rica coincides largely with the Talamanca range. (See Figure 5.) These form a complex conjugate pattern crossing the range at a high angle. The pattern is consistent with that expected by deformation due to the maximum horizontal stress perpendicular to the range. The faults in the vicinity of San Jose and Cartago are part of this general pattern.

The region west of Cartago was examined in some detail, because of the significance of destructive earthquakes near a feature called the "Cartago Fault". This is reported to lie along the Rio Navarro Valley, but to our knowledge has not been positively identified in outcrop. The trace of the proposed fault zone was examined and no positive evidence was found for its existence as an active feature. In one locality, where a long section of the river valley trends across the feature at right angles, the escarpment was examined in great detail. No active fault cuts that particular terrace.



A series of gravity transects across the Navarro River Valley were carried out next, to see whether there were significant changes in rock densities across it that might indicate the presence of a significant fault at depth. Conclusions are that the gravity results showed no convincing evidence for significant faulting at those locations.(12) If a major fault does exist, the density of the rocks must change very little across it.

Near the western end of the Rio Navarro valley, Mr. Alvaro Aguilar examined both the geology and seismicity, as part of a thesis for UCR.(13) This field area was also examined by UCSC staff and their observations support Mr. Aguilar's conclusions that the microearthquake activity in that area occurs along several small faults that intersect the Rio Navarro Valley at a high angle. In addition to this, it was noted that lines of hydrothermal springs in the area trend across the Rio Navarro rather than along it. That could indicate the presence of other active fault zones as well.

A major fault scarp occurs near the town of Alajuela, and this feature is called the Alajuela Fault. The scarp is prominent and can be easily seen from San Jose. Several gravity transects across the fault were run with mixed results. Two of the transects showed a change across the fault, while a third did not. At best this indicates that in complex volcanic terrain, gravity observations do not produce definitive results concerning the presence of minor fault zones.

C. Summary

While our results to date are not final or definitive, we can draw several preliminary conclusions: 1) Faults in the Talamanca range are likely to be small, and active faults may have a variety of structural trends; 2) the "Cartago Fault", thought to be responsible for considerable damage in the past decade, may not exist as such. Instead earthquakes may be generated on any of a number of smaller faults, making precise prediction very difficult; and 3) many of the methods established for study of large fault zones elsewhere, such as the San Andreas of California, may not be of high value in the Talamanca range. New tools may

be needed to study this region. The combination of microseismicity, a variety of remote sensing techniques, and local field work on better defined objectives, may prove to be helpful. The complex conjugate fault pattern that seems to characterize the Talamanca Range is consistent with that expected as a result of collision of Costa Rica by the Cocos Ridge offshore to the west. With this mechanism, the observed pattern of faulting, and our present limited state of knowledge, there is no reason to assume that seismicity should be restricted to any one locality along the range.

VOLCANOLOGY

The volcanological aspect of the Project has had two foci: day-to-day geophysical and geochemical monitoring of five volcanoes, (Irazu, Poas, Turrialba, Arenal and Rincon de la Vieja); and, a geologically-based assessment of volcanic risk at two of these, Turrialba and Arenal. (See Figure 6.) Each focus has yielded short-term results, but each is only partially completed.

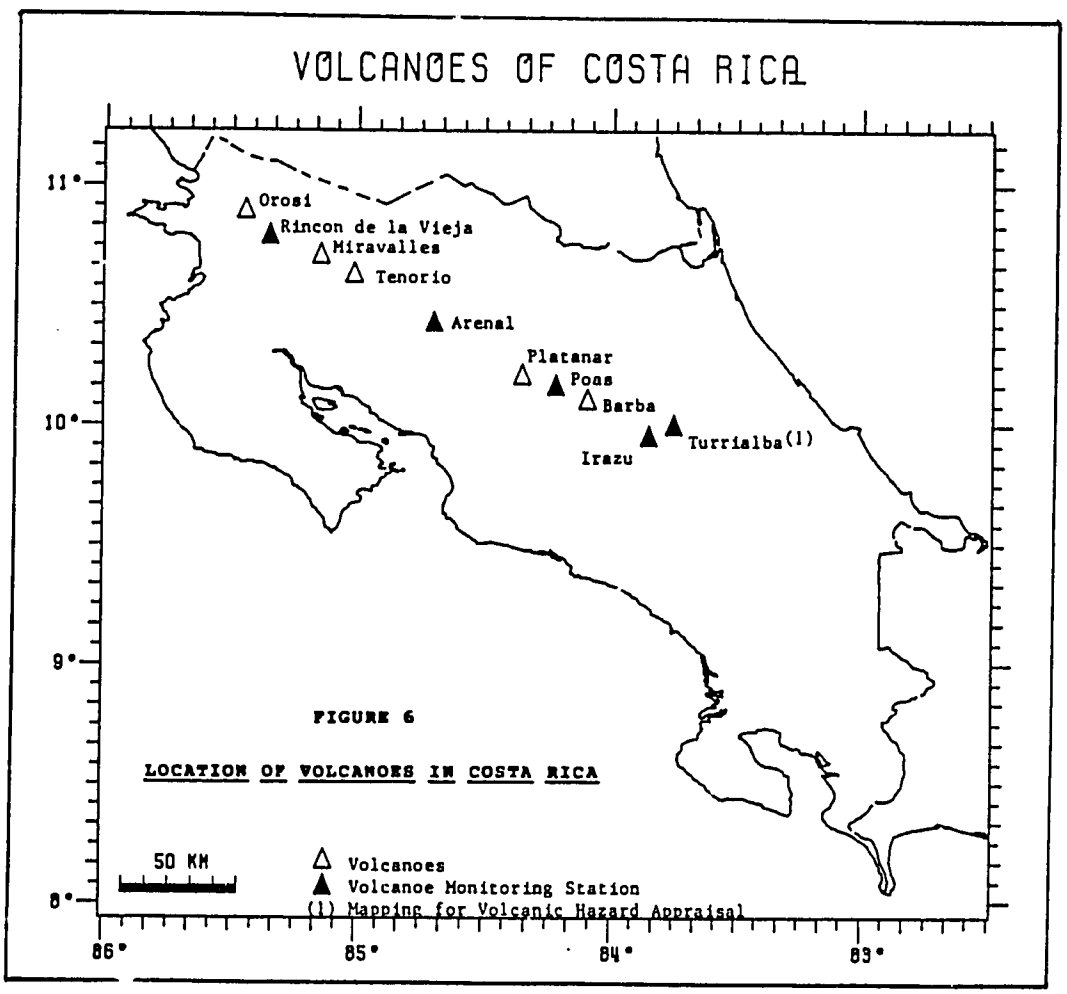


FIGURE 6

LOCATION OF VOLCANOES IN COSTA RICA

A. Geophysical Monitoring

Volcano monitoring for this Project uses several methods: 1) surveying, 2) seismicity, 3) tilt, and 4) temperature measurements and chemistry of gases and erupted materials. The objective of the volcano monitoring program

is to have a first-rate routine monitoring program which is fully supported in Costa Rica operational by the end of 1987. Significant equipment purchases remain to be completed, especially for telemetry of tilt data, but, the chief need now is for training of Costa Rican personnel in data interpretation.

1) Surveying

Surveying networks, involving about ten stations per volcano, have been laid out at each Irazu, Poas, Arenal, and Turrialba to assess patterns of ground deformation; large inflations or deflations often preceding eruptions. The networks are resurveyed quarterly using equipment purchased by the project. Initial data, developed through May 1984, were brought to UCSC and the Cascade Volcano Observatory (CVO) in June by Eduardo Malavassi for review and interpretation. No consistent pattern was found. This negative result probably means no eruptions are imminent, but may also indicate a need for improvements in data gathering techniques or the siting of stations. Routine measurements and data reduction by UNA staff seem satisfactory and with further training they can interpret their results with greater confidence.

2) Seismicity

Seismograph stations have been installed on Irazu and Poas and seismicity is monitored constantly. Current levels of seismic activity are low, confirming the results from the surveying work, that no eruptions are imminent. Further research on volcano seismology should be of three kinds. First, permanent stations are needed at Arenal and on Turrialba. Second, a portable unit of seismometers needs to be operated at each volcano for several months to obtain baseline data against which to assess changes in activity, to determine the depth of sub-volcano earthquakes, and to search for evidence of magma at depth. For example, during the volcanic crisis at Arenal in June 1984, no reliable portable array was available in-country and there was no background for evaluating whether measured earthquakes were atypical in number, intensity, or type. Third, Costa Rican personnel should receive training in the interpretation of volcanic earthquake data so they can better analyze the data they are currently obtaining.

3) Tilt

Tiltmeters have been purchased by the Project for installation on the four regularly monitored volcanoes. Such measurements supplement the surveying results, but are more sensitive and can be recorded continuously. Installation has been postponed until fiscal and technical decisions are made concerning how to record and transmit the data. Successful installation of tiltmeters requires solving two problems: first, how to select and protect sites of the instruments so that tilts reflect volcano inflation or deflation rather than ephemeral surface phenomena (slope instability, rainfall, etc.); and second, how to record or transmit data, for example using on-site paper records or telemetered digital information. (At this time, two experimental sites have been installed at the Arenal and Irazu volcanoes.)

During 1984, Eduardo Malavassi and Jim Gill consulted widely with other volcanologists concerning these problems and suggested the following solutions. First, regarding siting, it is suggested that Ken Yamashita, currently in charge of ground deformation monitoring at the USGS Cascade Volcano Observatory, visit Costa Rica to advise on site selection and installation. Yamashita would also help to bring computer programs into operation for the correction and reduction of tilt data. Second, regarding data transmission, it is suggested that a subcontract be made to a geophysical systems group to develop a relatively low-cost telemetry system of digital output to a central, computerized storage site.

4) Temperature and Chemistry

Volcanic gases are sampled and fumarole (vents for these gases) temperatures are measured on a routine basis by NA UNA staff. Chemical analysis of the key components of these gases (i.e., amounts of sulfer dioxide, fluoride and chloride) are done on a routine basis at UNA to predict volcanic behavior. Primary efforts for these measurements have concentrated on Poas, though Turrialba, Irazu, and Arenal are also measured. It is suggested that Jorge Baquero spend two weeks at the Cascade Volcano Observatory with Tom Cassadaval working on gas monitoring techniques.

The final type of volcanic monitoring has been the analysis of the chemical composition of lava being erupted from Arenal. (See Appendix F.) During 1984, twenty samples which had been erupted from 1968 to 1984, were analyzed at UCSC for the concentration of twenty-three elements; key samples were also analyzed for the isotopic composition of oxygen (O), hydrogen (H), and thorium (Th). The resulting interpretation is almost complete and will be available during 1985.

It is believed the eruption of Arenal was caused by the intrusion of new magma into an already-filled chemically differentiated chamber. As a result, the pre-existing magma erupted explosively and fatally in 1968. Mixed magma was eventually erupted beginning in 1973. Since then, the composition of the mixed magma has been changing and is approaching the chemical composition of what erupted explosively earlier. This change has increased the viscosity of the magma, making future explosive eruptions more likely than at any time since 1968. It is likely that small volcanic crises, such as that in June, 1984, will become more common before the eruption terminates. It is unlikely though, that Arenal will approach the explosivity it had in 1968, because recently obtained hydrogen isotope and water content data suggest that Arenal's magmas are being increasingly degassed.

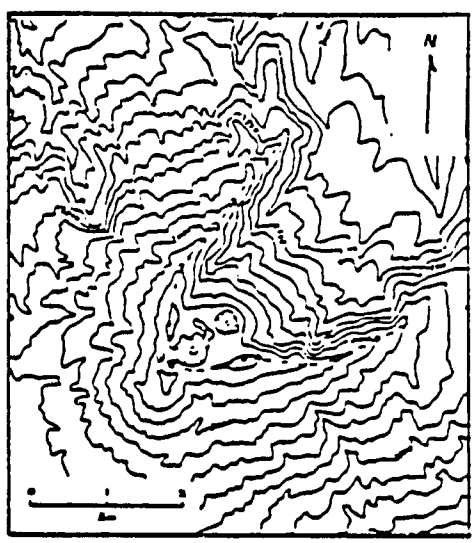
Joint fieldwork undertaken by M. Reagan and E. Malavassi evaluated the possibility of assessing volcanic hazards at Volcan Arenal by analyzing previously erupted tephra. It was concluded that a great potential exists to analyze the data to forecast future events. This is a necessary step toward hazard evaluation in Costa Rica and increasing local involvement in such studies.

B. Geologic Risk Assessment

Knowledge of the recent past is the best guide to the near future in volcanology. Consequently, geological mapping of all the high-risk active volcanoes is needed. Because some such data were available for the crater areas of Irazu and Poas, the project focused first on the last 10,000 years of history at Volcan Turrialba, which last erupted in 1864 and might be "overdue".

During the winter of 1984, the geology of the crater of Volcan Turrialba was mapped by a U.S. graduate student. (See Figure 7.) Approximately eight lava and tephra samples (fragmental volcanic material) were mapped, measured, and collected from the volcano. The summit area of the volcano was mapped in detail and the history of events recorded within its crater was determined. About fifty rocks have been studied microscopically and have been chemically analyzed; four charcoals and one lava have been dated radiometrically. An interim report has been sent to UNA and is summarized here. A complete report awaits a second field season and further laboratory work, planned to be done by December, 1985.

FIGURE 7



TOPOGRAPHY OF VOLCAN TURRIALBA

Of all of the elements analyzed in this study, silicon dioxide (SiO_2) is the most fundamental in characterizing volcanic deposits. The physical properties of magmas relate to their silicon dioxide (SiO_2) content. Magmas low in silicon dioxide have low viscosities and high densities while the opposite is true of magmas containing large amounts of SiO_2. The higher the silicon dioxide content of magma the higher the potential for explosiveness. Rocks

analyzed for the Project were found to contain varying degrees of silicon dioxide. Table 2 indicates common percentages of silicon dioxide contained in several types of rock.

TABLE 2

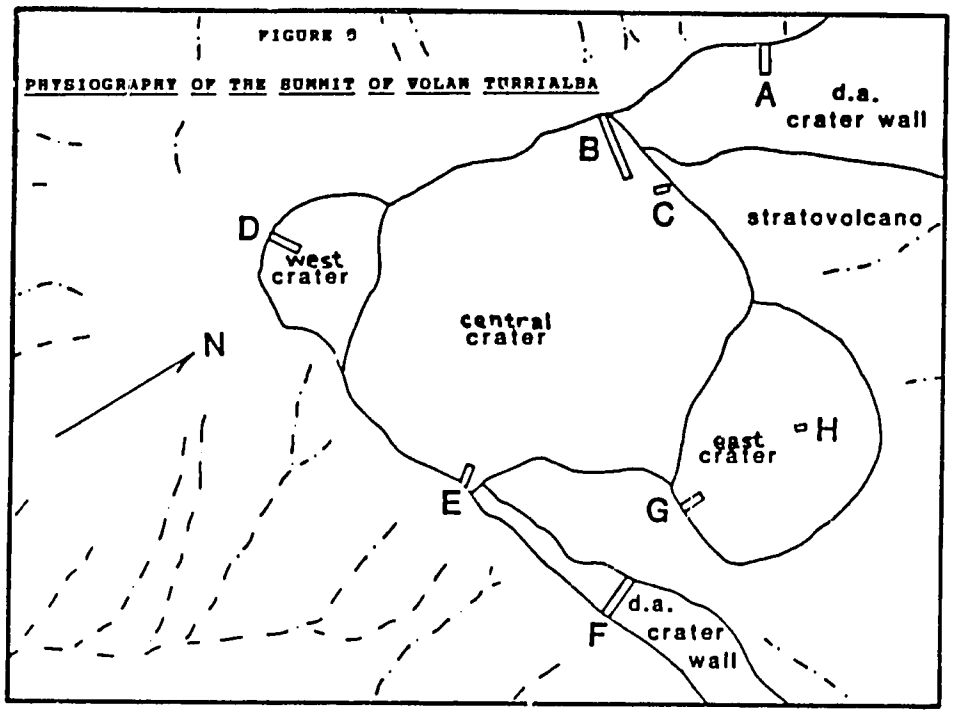
SILICON DIOXIDE (SiO_2) CONTENT OF COMMON VOLCANIC ROCKS

Basalt	SiO_2 = < 53%
Basaltic andesite	SiO_2 = 53-57%
Andesite	SiO_2 = 53-63%
Silicic andesite	SiO_2 = 57-63%
Dacite	SiO_2 = 63-70%

Based on stratigraphic analysis, at least thirteen eruptions and one debris avalanche event are recorded in the crater and summit region of Volcan Turrialba. Four major eruptions have occurred during the last 2500 years, with the oldest of this series having been a large, highly destructive eruption of silicious andesite. The entire region around Volcan Turrialba was devastated and part of the heavily populated Central Valley was covered with tephra deposits. (Appendix G shows a newly revised view of the stratigraphic relationships in the crater of Volcan Turrialba.)

Initial interpretation indicates that between 2,500 years ago and approximately 10,000 years ago, Turrialba experienced a major event during which 1 to 2 km^3 of the volcano collapsed toward the northeast. (See Figure 8.) The resulting avalanche devastated areas up to ten kilometers from the volcano, and has left the northeast sector at highest risk for future debris avalanches. A smaller stratovolcanoe was subsequently built inside the crater. Most of the stratovolcano, built from alternating layers of fragmental material and lava sheets, is constructed of lava flows, although one or two of its eruptions sent out tephra deposits that are found around the summit craters of Turrialba.

Volcanic rocks which erupted after 2,500 years ago generally decrease in silicon dioxide content in time as compared with earlier erupted materials. Four eruptions followed the construction of the main portion of the stratovolcano. The first occurred approximately 2500 years before



present. It was a highly destructive eruption of silicic andesite (SiO_2=57%-63%) that devastated much of the western part of central Costa Rica. The second erupted basaltic to silicic andesite tephra deposits (SiO_2=53%-63%) , found both within the craters of Turrialba and on the flanks of the stratovolcano; the third produced a small lava lake of basaltic andesite (SiO_2=53%-57%) in the East Crater; and the fourth, which occurred in 1863-1865, produced basaltic tephras (SiO_2 < 53%) that are found throughout the Turrialba area.

The general decline in silicon dioxide with time since the eruption of the silicic andesite pumice has implications for the volcanic hazards potential of Volcan Turrialba.[14] Changes in the chemical composition of the most recently erupted material seem to indicate that eruptions in the immediate future will be similar to that of Irazu in 1964 which was an explosive eruption of basalt, but its size will be hard to predict. That is, ash fall and lavas may seriously affect the Central Valley, but hot avalanches are unlikely in the region between Volcan Turrialba and Cartago, and though they could affect the region immediately surrounding Turrialba, recurrence of the major eruption of 2,500 years ago is also unlikely.

The possibility of another debris avalanche occurring during an eruption at Turrialba is everpresent, no matter what the silicon dioxide content of the erupting material. Three factors combine to increase the potential for a debris avalanche at Turrialba. It has steep sides, an extensive hydrothermally altered core, and is in an area of heavy rainfall. If seismicity should start at Turrialba, indicating magma movement underground, tilt should be monitored closely, because any inflation of the Turrialba volcanic edifice would increase the likelihood of a debris avalanche.

During 1984, facilities for radiometric dating of Costa Rican lavas were developed at UCSC and preliminary measurements made on rocks from Turrialba, Arenal, and Irazu. The Turrialba sample is from the caldera wall and seems to be older than 6000 years. Project staff's prediction that Turrialba and Irazu would be well-suited to dating by these methods has been partially confirmed, and more definite age determinations for Turrialba are in progress. A Costa Rican student in residence at UCSC would increase project staff to help prepare and run samples, thereby speeding the results of this part of the Project.

C. Summary

Work on the short-term geophysical and geochemical monitoring of volcanic activity and the long-term geological assessment of volcanic risk has proceeded according to schedule. Poas and Irazu remain relatively quiet, although the high temperatures and the chemistry of fumaroles at Poas indicate that magma is nearby. Arenal is likely to become somewhat more explosive in the near future. Turrialba experienced a major eruption about 2,500 years ago. The explosiveness of Turrialba has since declined and it is currently unlikely to be more hazardous then Irazu. Some equipment purchase remains necessary, but the principal need during 1985-1987 is for training of Costa Rican personnel in the volcanological aspect of the Project, and completion of the volcanic risk assessment of Volcan Turrialba and Arenal.

SYNTHETIC ACCELEROGRAMS

Costa Rica is a complex tectonic region because of the intersection of three of the earth's crustal plates in this area. The mechanical interaction of the plates leads to different types of earthquakes, each producing different types of motion according to its source mechanism.

A primary task of this Project is to predict typical amplitudes of the wave motion that result from different types of hypothetical earthquakes in Costa Rica. Through this process, synthetic accelerograms are developed which could be used to initialize the generation of quantitative data to assist engineers with design criteria to protect newly built Costa Rican structures.

A. Computer Modelling

A computer program has been developed to compute acceleration, velocity and displacement of the ground as a result of an earthquake. Results can be given for design purposes, either as time histories or as frequency spectra. All three components of ground motion, radial, vertical, and tangential are computed as is the decrease in amplitude along the path of the earthquake. Attenuation values are assigned to each of the layers of the crustal model used. There is no limitation to the number of layers or geologic strata that can be included.

The computer program includes different types of standard source time functions, including multiple events. At this stage, source effects such as the direction of the motion from the epicenter is approximated by using a point source, and then appropriately corrected for the propagation of the event through the earth's crustal layers. The effect of the layered crust below the receiver is completely calculated by a matrix propagator algorithm, thus it includes all possible interactions and wave-type conversions in the stack of layers.

Crustal Model

All of the mechanisms which generated the earthquakes for the following five figures are located in the upper three layers of the earth's crust. The first layer, composed of soft volcanic sediments is 1 km thick, the second granitic upper crustal layer is 5 km thick, and the third lower or base of the crustal layer, which is composed of granodiorite rocks, is 25 km thick.

Strong Motion Waves

To understand what is occurring during the movement of an earthquake, the motion is decomposed into its three components: Vertical, radial, and tangential. Most waves are P-waves. Radial and tangential waves are abbreviated as SV or SH waves. Vertical waves (P) have an up-and-down motion while radial and tangential waves (SV and SH) move the earth in a horizontal motion. Radial waves move from the source, in one direction, and tangential waves move perpendicular to the radial waves.

Waves propagate through the earth to a place and it is this movement that is being measured. P-waves are not very important in terms of seismic damage since buildings are often constructed to withstand the pressures exerted on them by their own weight. Most structures in Costa Rica will withstand as much as two or three times a buildings own weight during vertical movement. Many of the buildings in Costa Rica have less resistance to movement from the lateral or horizontal waves generated by an earthquake. Therefore, it is the horizontal waves (SV and SH) which are the most destructive waves and, therefore, the motion they represent is of primary concern to this Project and Costa Rica.

Earthquake Mechanisms

There are three different types of typical earthquake mechanisms which were used to generate the following five accelerograms: common subduction, when one plate overrides the other; strike-slip, where the two plates remain on the same horizontal plane, yet move in opposite directions; and normal faulting, where a separation between two plates occurs and one moves upward and the other moves in a downward motion. Each mechanism produces a different kind of horizontal, vertical and radial wave motion pattern. The mechanisms of radiation, or motion at the source of an event, will be reflected to a receiver, such as a strong motion station. Their motions are then represented by the tangential, vertical, and radial wave patterns for both P- and S-waves. The accelerograms represent these different wave motions for each earthquake event depicted in the figures of this section of the report. (See Page 40-42.) Each figure contains four diagrams corresponding to vertical P, vertical P and SV, radial P and SV and tangential SH waves.

Examples

The accelerogram examples shown in Figures 9-13 were selected to realistically cover the most typical combination of the different types of motion and attendant force which can be expected in Costa Rica. Each figure shows a combination of a source, the hypocenter, and the path or trajectory of the movement toward the cities of Costa Rica. Of the five earthquakes presented, three are large (M_S = 7.5) subduction events and the other two are smaller (M_S = 6.5) strike slip events likely to be indirectly related to subduction. The accelerograms for the large subduction events are at 20 km deep with observation points 50 km away in three different directions, (see Figures 9-11), and the smaller shallower events are at 6 km deep and have observation points at a 12 km range (see Figures 12 and 13). In these synthetic accelerograms the distance is approximately fifty kilometers as this is a typical distance that most subduction events would have to travel inland to reach the cities where most of the population lives.

FIGURE 9

ACCELEROGRAM OF SUBDUCTION EARTHQUAKE

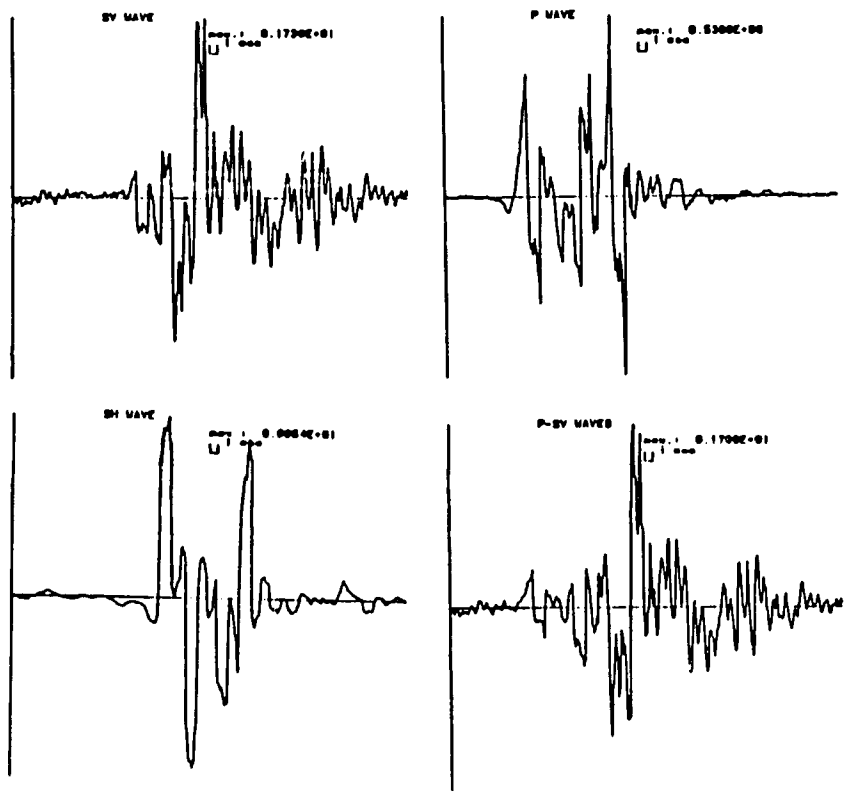


FIGURE 10

ACCELEROGRAM OF SUBDUCTION EARTHQUAKE

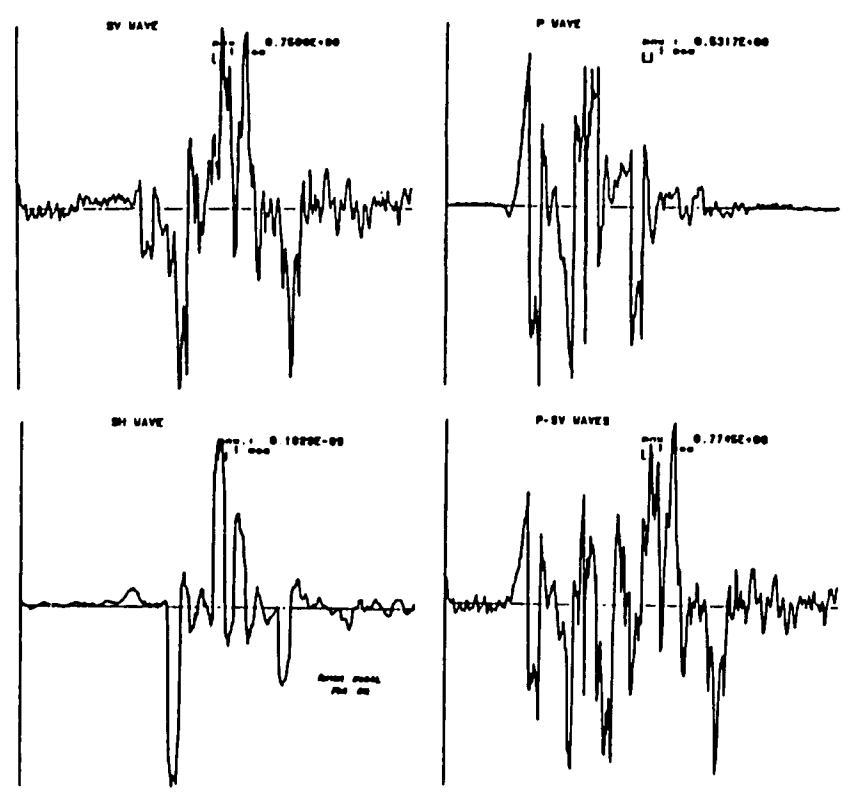


FIGURE 11

ACCELEROGRAM OF SUBDUCTION EARTHQUAKE

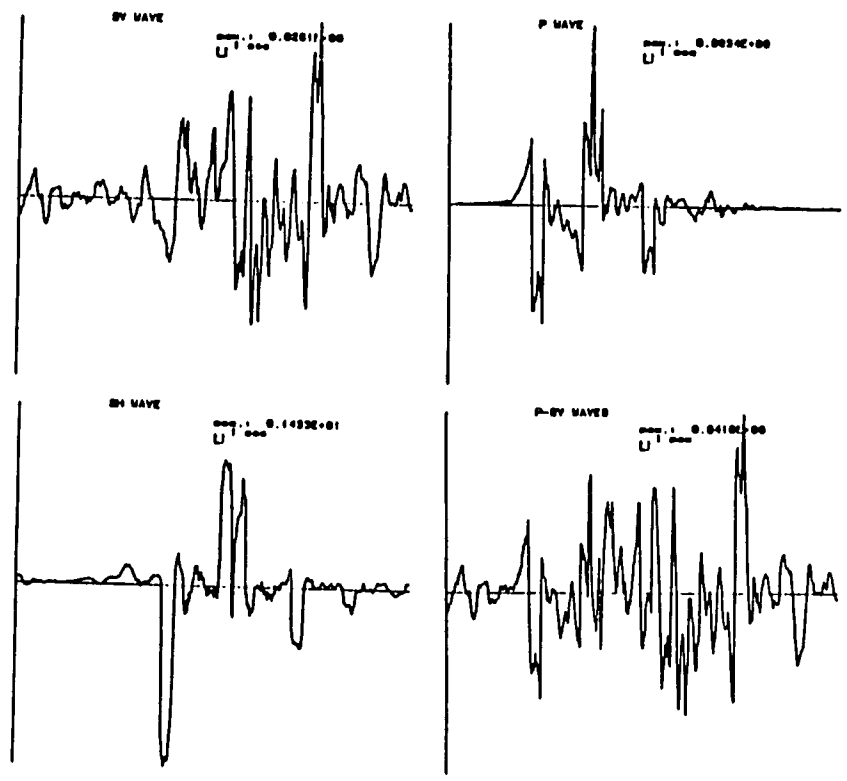


FIGURE 12

ACCELEROGRAM OF STRIKE SLIP EARTHQUAKE

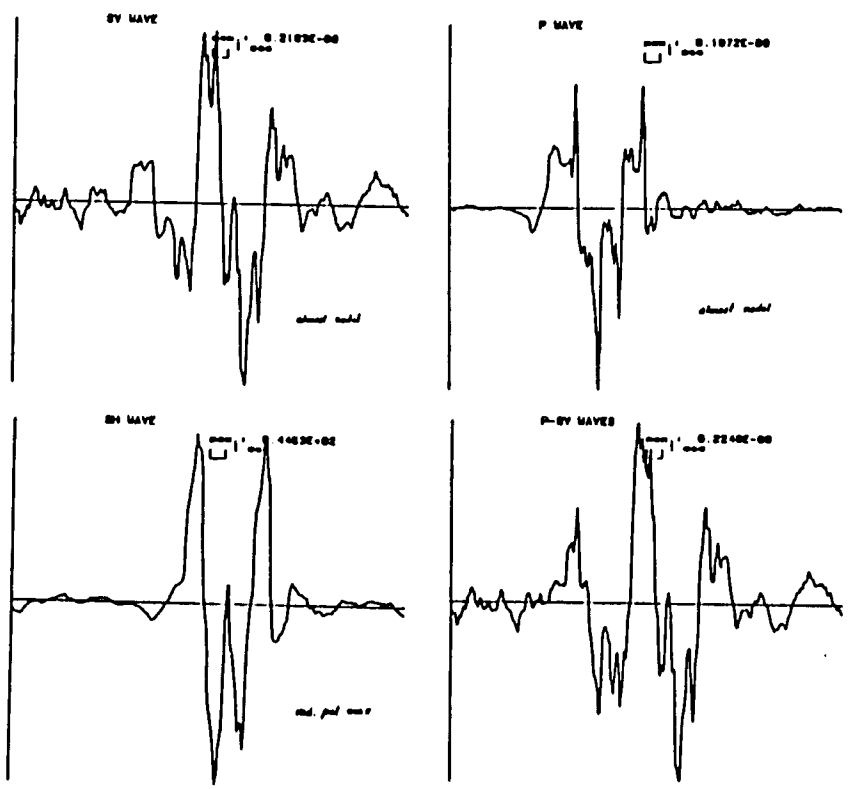
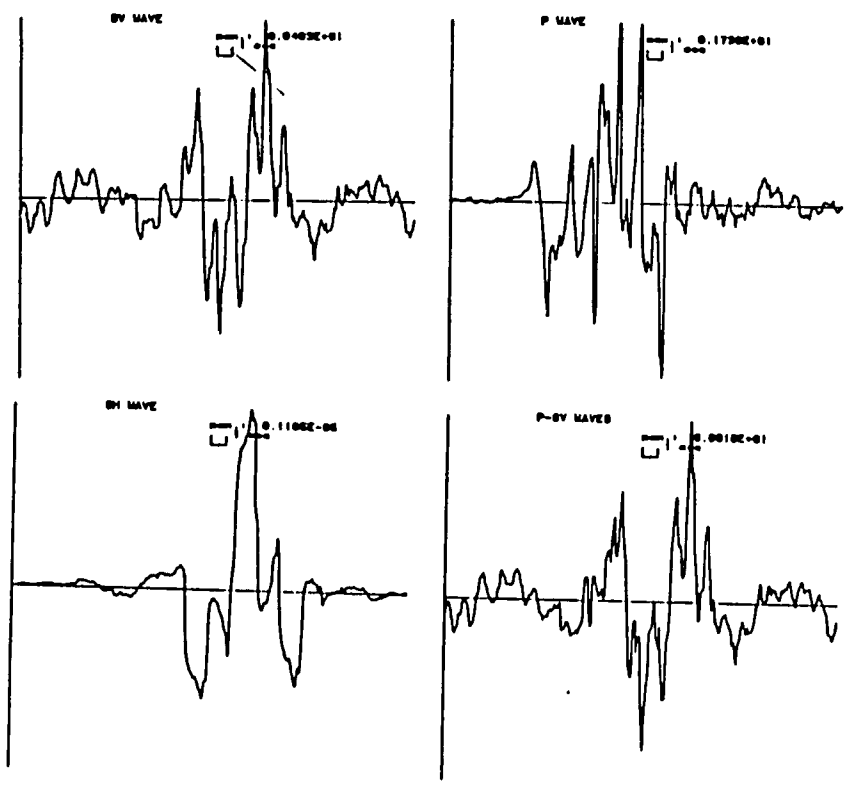


FIGURE 13

ACCELEROGRAM OF STRIKE SLIP EARTHQUAKE



B. Accelerogram Analysis

The most important result is that the largest computed acceleration occurs for the shallow strike-slip event on the horizontal (transverse) SH wave, even though this event is one order of magnitude smaller than the largest subduction event. This is expected since the motion of earthquakes with a typical orientation parallel to the offshore trench will have nodal and almost nodal directions towards the northeast for both vertical and horizontal waves, whereas the northeast direction from the trench coincides with the strongest SH radiation by a strike-slip mechanism.

The local geology strongly contributes to the characteristic complexity and reverberation-like aspect of the vertical (P) and horizontal (SV) waves. This is due to the multiple P-SV conversions typically occurring in multilayered media. The transverse (SH) waves undergo no such conversions, and this is clearly seen in all transverse (SH) accelerograms.

All these characteristics of the induced local ground motion are extremely important in the estimation of probable seismic intensities and duration of ground shaking, as well as in the quantitative assessment of the maximum kinetic energy and ground displacement to be expected at a given site.

Design spectra can thus be estimated from a more realistic basis which includes the effects of multiple parameters. Of course, the computer program will be extremely useful when actual accelerograms are recorded, since they provide the investigator with the opportunity of calibrating the model parameters by directly modeling the observed recordings. If earthquakes of moderate magnitude ($M_S = 5$), which are a relatively common occurrence, are well recorded, the path effects can be very realistically deduced by this modeling process. Thus, the estimates of strong ground shaking due to much larger events can be predicted with increased certainty.

C. Summary

Theoretical accelerograms have been constructed to quantitatively assess the probable characteristics of strong ground motion due to earthquakes near populated and industrial areas of Costa Rica. The resulting computer generated simulation takes into consideration the typical directional, motion, and force parameters to be expected in the region, namely (1) low angle thrust faulting at crustal and subcrustal depths (subduction), and (2) strikeslip, thrust, or normal faulting at very shallow depths.

In Costa Rica, thrust faulting associated with the subduction process has historically produced $M_S \leq 7.5$ earthquakes, whereas shallow faulting has produced lower magnitude events. The ground shaking at a given locality, however, will also be dependent on the local geology, the decrease of the seismic energy with distance and, very importantly, on the radiation pattern of the earthquake.

The preceding theoretical accelerograms provide time and frequency estimates of the peak acceleration of typical Costa Rican earthquakes, the predominant period of oscillation, and the duration of shaking and relative amounts of strong ground motion as a function of faulting mechanisms.

What is of most interest to Costa Rican engineers who design structures in Costa Rica is the minimum and maximum variation of the acceleration of the different types of motion generated by an earthquake, particularly the horizontal (SV and SH) motion. The synthetic wave patterns generated by this project provide the first steps toward eventual protection of structures by engineering safety features directly into buildings at the onset of any planning and design phase. When the modeling begun here is completed, so that sound quantitative measurements can be assigned to the wave patterns, engineers will be able to design buildings in Costa Rica which can withstand the maximum horizontal pressures that could reasonably be expected to be radiated from typical earthquakes.

SEISMOLOGY

The following section on seismology covers three areas: a) earthquake potential, b) earthquake damage and intensity and c) seismicity and tectonics. The earthquake potential analysis reviews historic earthquakes which have occurred in Costa Rica in order to determine the damage such events would cause if they were to be repeated. The damage and intensity discussion compares the historical activity with more recent data to locate and visually render the intensity distribution of the most damage prone areas in Costa Rica today. The third part of the seismology section is a current analysis of synthetic waveforms, based on seismogram modeling, that show the tectonic framework of recent earthquakes in Costa Rica. Synthetic waveform modeling is a useful approach toward developing forecasting tools in Costa Rica.

A) Earthquake Potential Analysis

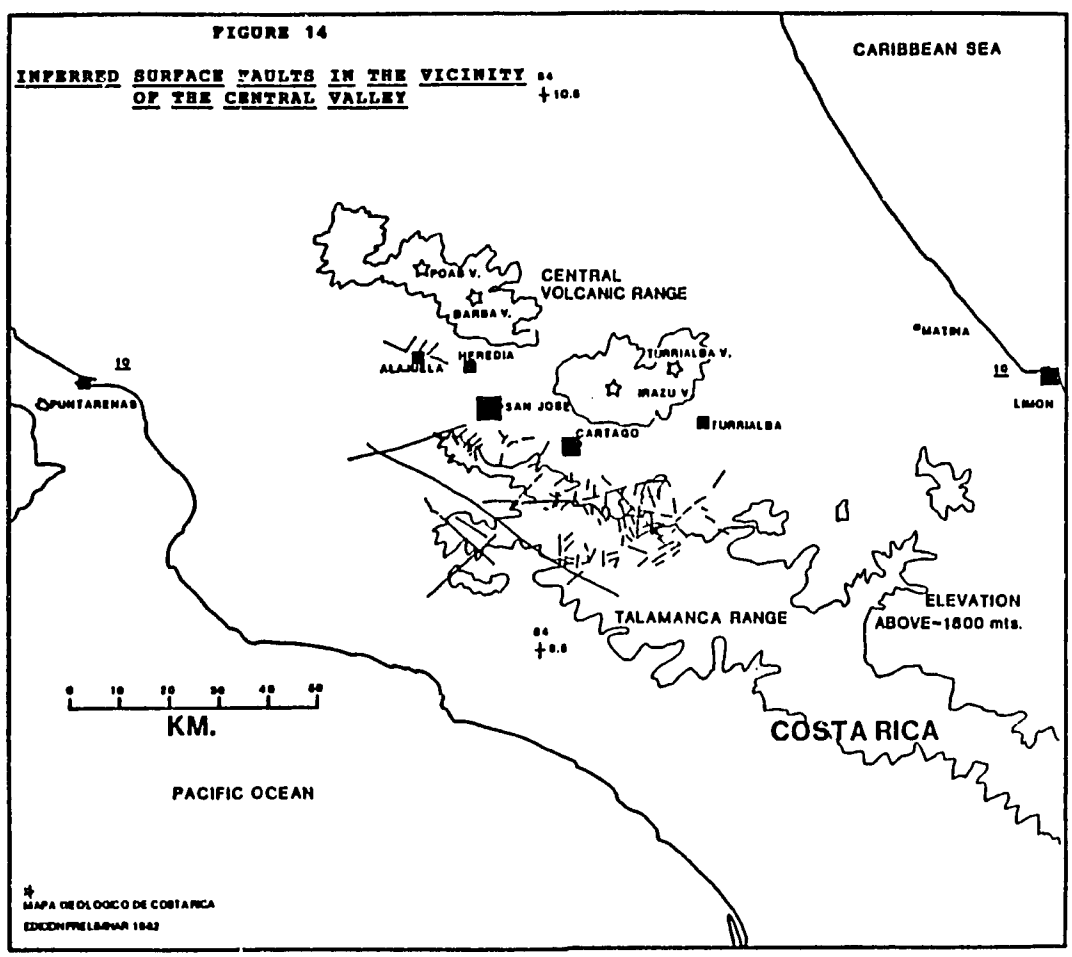
Four areas of importance are discussed in the following earthquake potential analysis: 1) The potential for earthquakes and damage from shallow surface faults in the Central Valley; 2) the potential for large earthquakes originating from the subduction zone at depths greater than the surface faults and for which the damage potential is unknown; 3) the potential for large ($M_s \geq 7.5$) earthquakes from an unknown source; and 4) other information on phenomena preceding large or damaging earthquakes in short to intermediate time periods.

1. The potential for earthquakes and damage from shallow surface faults in the Central Valley.

Several scientists believe that earthquakes along the shallow surface faults in the Central Valley (San Jose/Cartago) region pose the greatest seismic hazard for Costa Rica.[15] Project staff concur with this assessment for several reasons.. The largest percentage of the Country's population lives in this region, it is a center for transportation, communications, utilities, and government, and historic records show repeated cases of serious damage due to earthquakes.

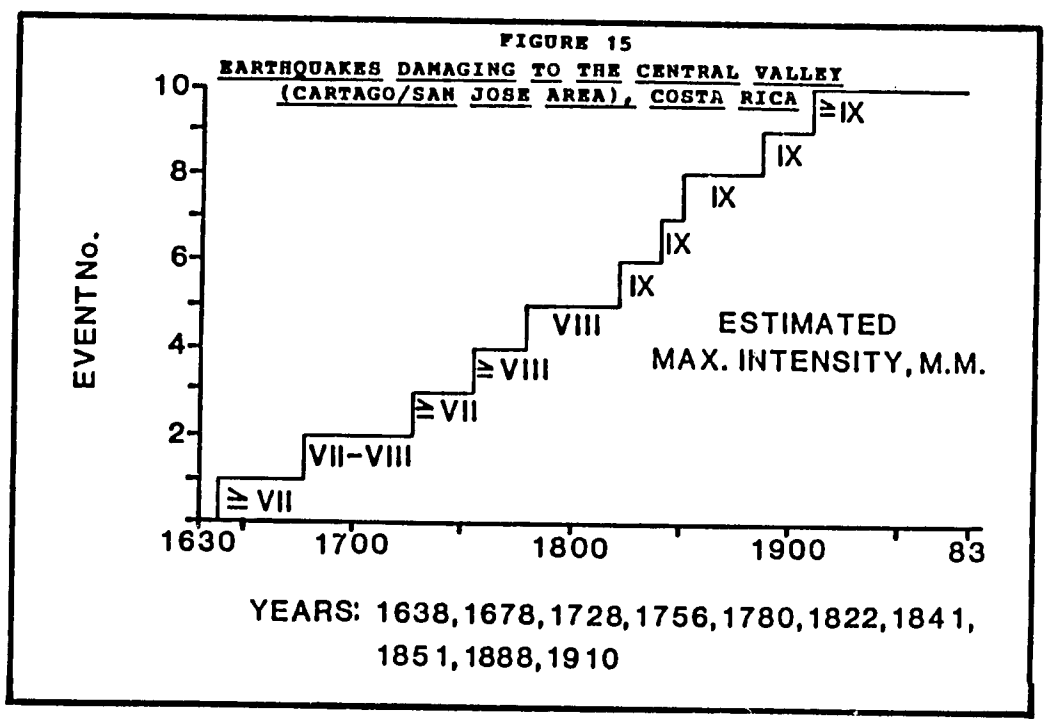
Identification has been made of earthquakes in the past which would cause serious damage to the San Jose/ Cartago area if they were to repeat in the future. The particular faults which produced these earthquakes are unknown; however, a distinct zone of faulting is found

in the Central Valley (Figure 14) which is a west-northwest-trending depression between the Talamanca Range (one of the highest mountain ranges in Central America) and the Central Volcanic Range, two parallel, major mountain systems in Costa Rica.



Any one of these faults, which are treated as a group, can break due to increasing stress and produce an earthquake which is damaging to the San Jose/Cartago area. The sequence of damaging historic earthquakes is shown in Figure 15. The estimated maximum intensity of historic earthquakes shows an increase with time, probably attributable to the increasing population

density in this area. As we stated earlier in the report, the probability for the next event to occur within the next three years, given that the last event was in 1910, is 30%, or about one chance in three.[16]



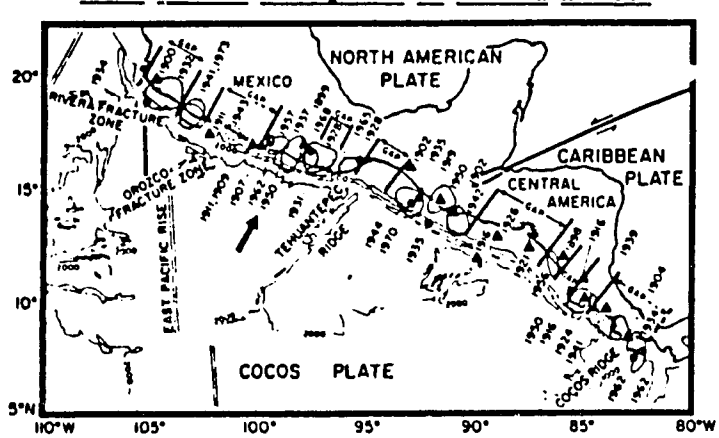
2. Potential for large earthquakes originating from the subduction zone at depths greater than the surface faults for which the damage potential is unknown.

McCann identifies the subduction zone under the central region of Costa Rica as a seismic gap in Category 2.[17] (See Figure 16.) This seismic gap region, not experiencing a large earthquake for a long period of time, has a fifty percent chance for the occurrence of an earthquake in the future, thus the designation of Category 2 by McCann.

As McCann discusses, the Middle America seismic zone has seven major areas that have not experienced shallow earthquakes larger than magnitude 7 for a minimum of 45 years. The southeastern end of the Middle America Trench, near the west coast of Costa Rica, is part of a complicated tectonic regime where the Cocos ridge intersects the trench. Large events which occurred in 1904 (M=7.3), 1934 (M=7.7) and 1941 (M=7.5) may have only partially ruptured the plate boundary. Carr and Stoiber (1977) suggest that prior to that the central region's last great earthquake occurred in 1851 and, therefore, McCann assumes the area has the potential for a great earthquake in the future and assigns the area to category 2.

FIGURE 16

RUPTURE ZONES AND EPICENTERS OF LARGE SHALLOW EARTHQUAKES IN CENTRAL AMERICA



Rupture zones (ellipses) and epicenters (triangles and circles) of large shallow earthquakes (after KELLEHER *et al.*, 1973) and bathymetry (CHASE *et al.*, 1970) along the Middle America arc. Note that six gaps which have earthquake histories have not ruptured for 40 years or more. In contrast, the gap near the intersection of the Tehuantepec ridge has no known history of large shocks. Contours are in fathoms.

Carr and Stoiber (1977) also reach a strong conclusion regarding the seismic potential of this section of the subduction zone:

> "Most great Central American earthquakes occurred in two brief space-time progressions. During 1847-1851 great earthquakes ruptured the El Salvador, eastern Nicaragua, and two Costa Rican segments of the arc. During 1898-1902, the western Nicaragua segment, the three Guatemalan segments, and a

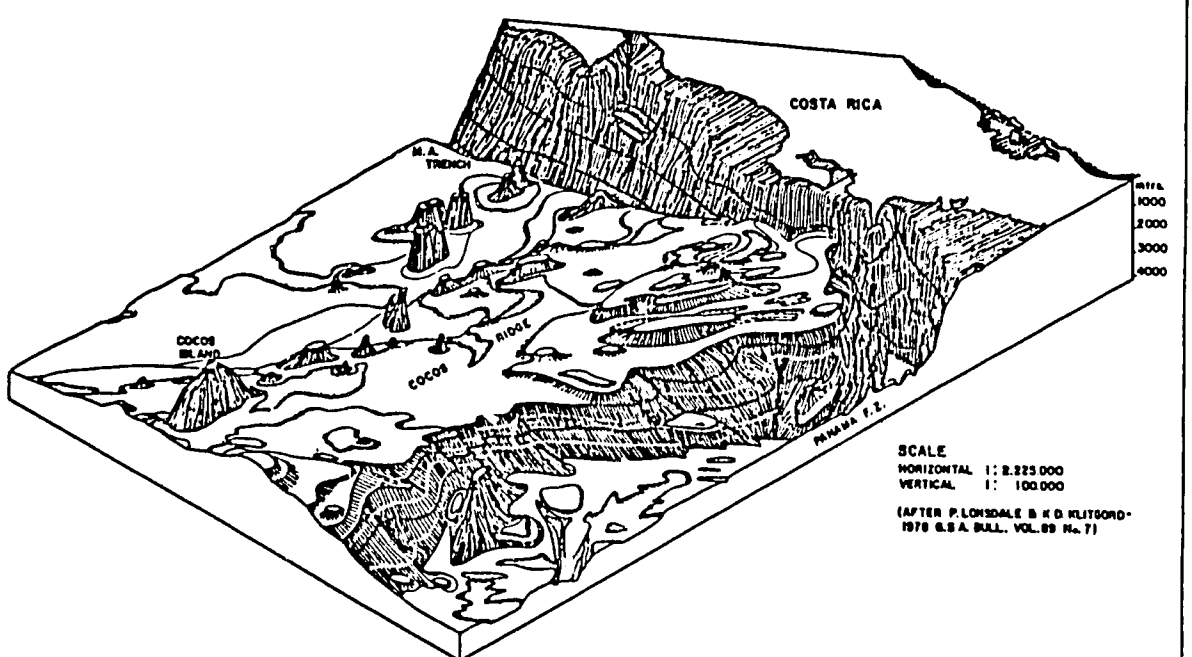
segment in southeast Mexico were ruptured. The most probable areas for the next great earthquake are the El Salvador and central Costa Rica segments of the arc."

Carr and Stoiber also state:

"...By considering the space-time distribution of just the great shallow earthquakes, we find that two segments in Central America are most likely sites for the next great earthquakes. These segments last ruptured at least 125 years ago, whereas all other segments last ruptured more recently. One is the El Salvador segment, ...the other is the central Costa Rica segment that last ruptured in 1851."

FIGURE 17

TOPOGRAPHIC RELIEF OF THE COCOS RIDGE



With respect to the subduction of the Cocos Ridge, as a perturbing characteristic for earthquake potential, a 3-dimensional figure of the topographic relief of the Cocos Ridge, (Figure 17), has been constructed.[18] The greatest topography of the ridge, as seen in the present bathymetry, is being subducted under southern Costa Rica, not under the central region of the seismic gap.

P-waves of the 1983 earthquake (M_s=7.3) indicates seismic subduction in the southern region, based on synthetic seismogram computer modeling in the time domain. (See following section on Earthquake Seismicity and Tectonics.) It appears that large subduction zone earthquakes are produced all the way to the abutment with the Panama Fracture Zone and it is possible that a large ($M_s \geq 7.5$) earthquake could rupture the central seismic gap. Another possibility is that the central portion is subducting aseismically without producing earthquakes. In fact, we have not yet found evidence that the 1851 earthquake referred to by Carr and Stoiber was a subduction zone earthquake. To the contrary, it appears to be associated with shallow surface faults in the Central Valley complex. Therefore, no earthquake which has broken the seismic gap of subduction in the central region of Costa Rica is known to us and aseismic subduction cannot be ruled out.

3. Potential for large ($M_s \geq 7.5$) earthquakes, source unknown.

Earthquakes $M_s \geq 7.0$ are listed in Table 3 and shown in time-space projection in Figure 18. Several features of seismic energy release patterns are suggested by Figure 18. A prominent deficiency of earthquakes from 1953 to the present can be seen within the central zone. The seismic moment release within the central zone from 1900 to 1983 has been significantly less than that in the N-W and S-E zones.[19]

TABLE 3

SEISMICITY OF COSTA RICA 1898-1983, $M_s \geq 7.0$

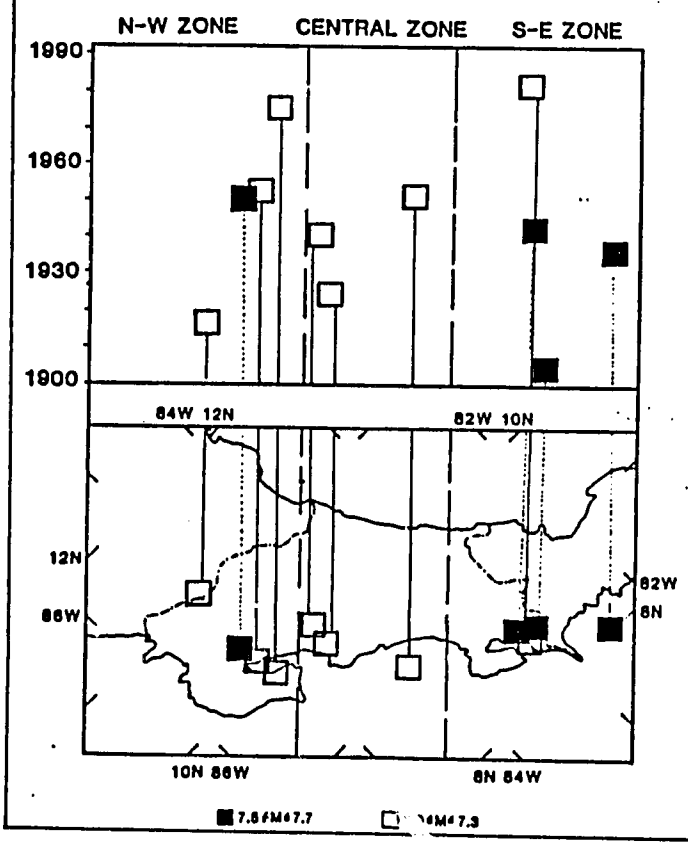
Year	Month	Day	Hour	Minute	Latitude	Longitude	Depth	Magnitude
1904[a]	12	20	05	44	08°30'	83°	25	7.3[2]
1916[a]	04	24	08	02	11°	85°		7.3[2]
1916[a]	04	26	02	21	10°	85°		7.3[2]
1924[d]	03	04	10	07	09°55'	84°30'		7.0[2]
1934[a,c]	07	18	01	36	08°08.4'	82°22.8'		7.7[4]
1939[a,c]	12	21	20	54	10°08.4'	84°37.8'		7.3[2]
1941[a,c]	12	05	20	46	08°40.2'	83°09.6'		7.5[1]
1950[a,c]	10	05	16	09	10°21'	85°12'		7.7[1]
1952[b,c]	05	13	19	31	10°18'	85°18'	32	7.0[1]
1952[b,c]	09	09	12	54	09°12'	84°12'		7.0[3]
1978[a]	08	23	00	38	10°03'	85°15'	48	7.0[1]
1983[a]	04	03	02	50	08°43.9'	83°06.9'	33	7.0[1]

a. USGS/NOAA listing
b. Miyamure (1976)
c. Kelleher, et.al. (1973)
d. Based on isoseismal work by Montero (pers. comm. 1982)

1. USGS/NOAA listing
2. Gutemberg & Richter (1954
3. Caltech & UCB
4. Near Panama/Costa Rica boarder; location uncertain, aftershocks in Costa Rica

FIGURE 18

TIME-SPACE PROJECTION OF COSTA RICA EARTHQUAKES, 1900-1983, $M_s \geq 7.0$



Earthquake magnitude, as a function of time, is shown in Figure 19. A remarkable quiet period from 1953 through 1977, can also be seen in this figure. (This might explain why some Costa Ricans have been startled by the recent resumption of earthquakes.) The question arises as to which rate of activity is most representative: That from 1904 to 1952, 1953 to 1983, or from 1904 to 1983, and whether, indeed the time period 1953 to 1977 is unusually quiet.

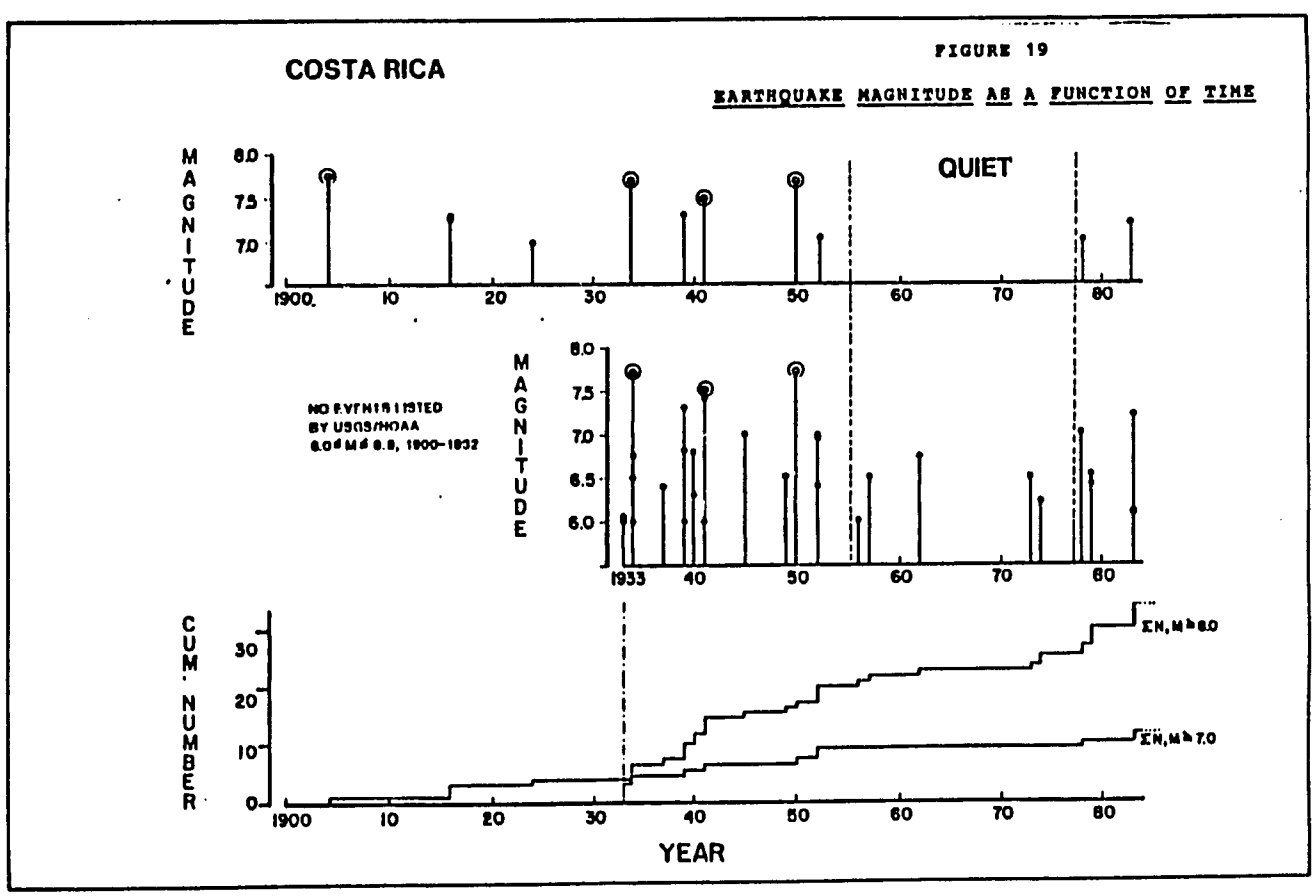


FIGURE 19

EARTHQUAKE MAGNITUDE AS A FUNCTION OF TIME

The seismic slip in N-W and S-E Costa Rica is less than half the plate convergence rates if the entire time period, including the quiescent period, is considered. The seismic slip only matches the plate convergence during the period of higher activity observed prior to 1953 and during 1978 and 1979. If seismic slip rates match plate convergence rates, this implies that the higher rate of earthquakes (prior to 1953) must be the "normal" background rate and that some "catch up" activity might be expected to compensate for the quiescent period from 1953 through 1977.[20]

Statistical patterns of earthquake rates indicate that whether or not one considers the quiescent period, an earthquake of $M_s \geq 7.5$ should be expected at this time. The fact that the number of earthquakes smaller than magnitude 7.5 has built up since 1978 appears to increase the likelihood of a $M_s \geq 7.5$ earthquake during the present time, relative to the period 1953-77. The source of an earthquake $M_s \geq 7.5$ is likely to be the subduction zone under Costa Rica.

Kasahara [21] and Toksoz have found crustal deformation rates based on geodetic data and earthquake migration patterns of a few tens to a few hundred kilometers per year. Based on the data, possible earthquake migration patterns which would be consistent with the range of crustal deformation rates would be comprised of earthquakes moving northwesterly along the length of Costa Rica between 1941 and 1952 (25 km/yrs.), and from 1904 to 1916 (27 km/yrs.), with the 1910 Cartago earthquake occurring along this trend. Crustal deformations at this rate might pass northwesterly from the April 1983 earthquake in the S-E zone to the southeastern edge of the central zone as early as about 2-4 years, given the uncertainties.

The seismic slip deficiency in the central zone points toward an earthquake (M_s>=7.0) in that region. The deficiency of earthquakes since 1953 suggests that an earthquake (M_s>=7.5) could occur anywhere along the length of Costa Rica.

To summarize our findings above, we believe that the Government of Costa Rica, should undertake a program of earthquake preparedness planning at this time for:

(1) A highly damaging, but moderate-sized, earthquake in the Central Valley (with damage expected in the San Jose/Cartago area at the level of maximum intensity (M.M.) VIII-X; and

(2) A large ($M_s \geq 7.5$) earthquake, probably located on the subduction zone, with damage potential unknown.

4. Other information on phenomena preceding large or damaging earthquakes in short to intermediate time periods.

Following is additional information, based on the Project staff's experience with other similar studies, that would tend to be consistent with the above assessments.[22]

Based on information gathered by C. Gonzalez (1910) it appears that foreshock type activity preceded the damaging earthquakes in Central Valley in 1888 and May 1910. All known data regarding foreshock sequences worldwide have been gathered. A characteristic 'envelope' indicates a drop in seismic activity following the peak rate of the foreshock sequence and prior to the mainshock. The 'envelope' of prior activity in Costa Rica is highly similar to the examples worldwide. This is very encouraging from the point of view of monitoring for earthquake precursors. For example, it is now known that the successful Haicheng, China earthquake prediction relied heavily on the occurrence of foreshock activity.

The April 1910 activity which preceded the May 1910 mainshock contained a strong earthquake, which caused significant damage, but is thought to have been smaller than the mainshock. Neither event was large enough to be listed by Gutenberg and Richter; it is guessed that the mainshock was M=5.5. Based on the isoseismal patterns it appears that the prior activity in April was 10 km west of the mainshock in May. Both

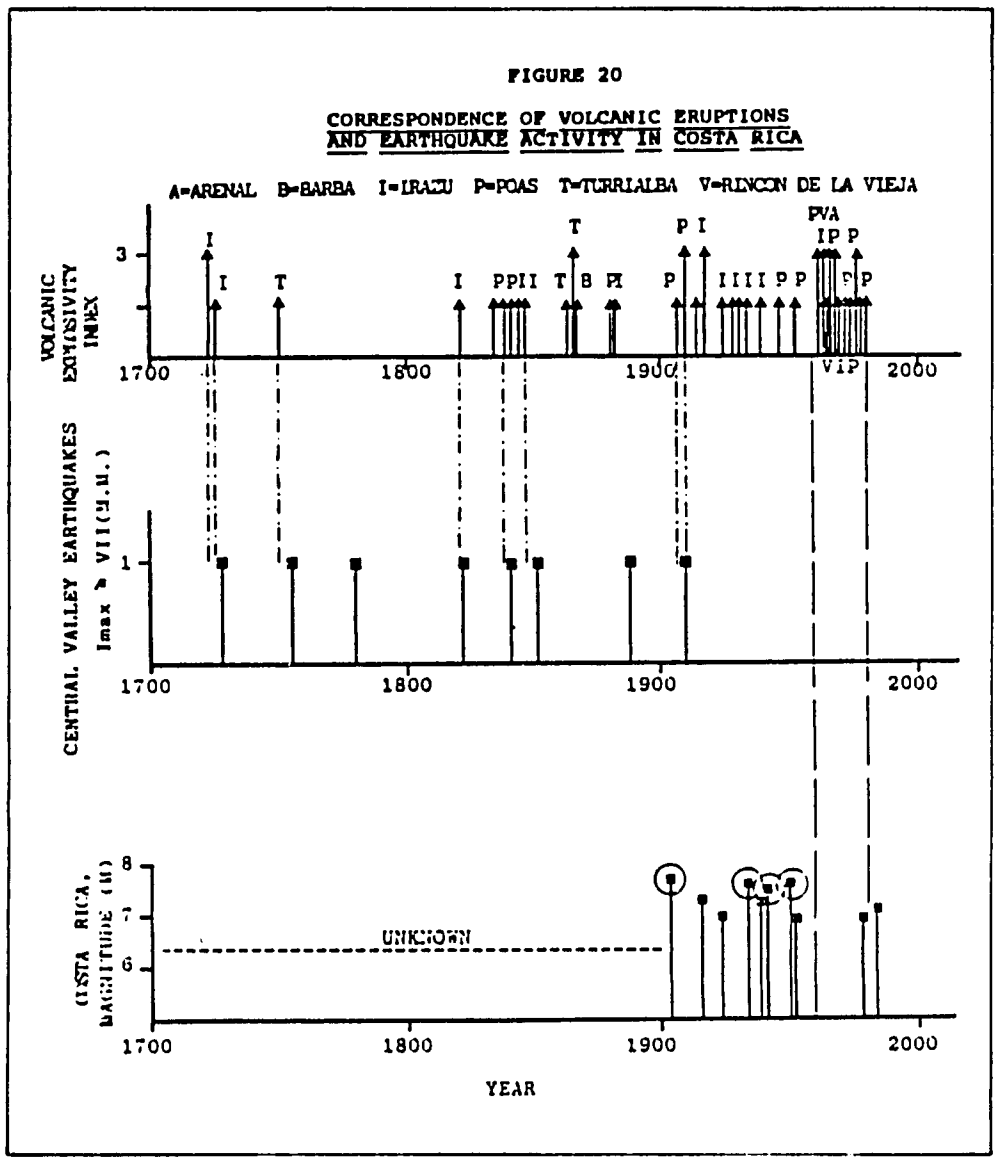
regions were found to be devoid of small earthquake activity for the time period of study (7/1976 to 6/1979). Although detailed information does not exist, the impression of Costa Ricans is that these regions have been quiescent in the long term. In May 1983, a series of three to four earthquakes (with the largest event M=3-3.5) occurred in the western quiescent zone which was the site of the April 1910 activity preceding the mainshock in May 1910. In addition, the region near Irazu and Turrialba became active, with swarm sequences in June and September 1982.

More definitive data are needed, but given the existing information it appears that seismicity is building up in the Central Valley region. This is suggestive of a stress build-up which might be associated with a repeat of a Central Valley event on shallow surface faults and similar to the historic events in 1841, 1851, 1888 and 1910.

A stress build-up in this region might also be expected prior to a large earthquake $M_s \geq 7.5$ along the subduction zone. The only detailed information which we have from Costa Rica is consistent with one general aspect of the Kanamori model, which assumes that "a creep-like slow deformation takes place at depth preceding the occurrence" of a large earthquake.[23] Our detailed relocations of the seismicity prior to the 1978 Samara, earthquake (M_s=7.0) indicates a concentration of activity inland and at the down-dip edge of the subsequent rupture zone.

Patterns of volcanic eruptions were examined in order to see if there is any correspondence with the earthquake activity.[24] The known volcanic activity from 1700 to 1980 is shown in the upper graph of Figure 20. The reporting of activity is not uniform with time; reporting improves most recently. The significance of activity is indicated as Volcanic Explosivity Index (VEI), with level 3 as the most significant and all other eruptions (VEI < 3) as less significant (shown with lower symbol height in Figure 20).

The middle graph in Figure 20 indicates the times at which damaging earthquakes have occurred in the Central Valley. The exact sizes of these events are unknown, thus all event symbols are of equal height.



The bottom graph in Figure 20 indicates the times and magnitudes of large earthquakes ($M_s \geq 7.0$) in Costa Rica from Table 3 with circled symbols indicating $M_s \geq 7.5$.[25]

The volcanic activity (upper graph) is first compared with the occurrence of damaging earthquakes in Central Valley (middle graph). We choose a time window of 5 years for volcanic activity prior to Central Valley earthquakes for initial tests which are reported here; other time windows will be tested in future work. The choice of a 5 year period is mainly arbitrary, but is of interest due to the relatively high probabilities for earthquakes within the coming few years.

In order to avoid a biased statistic we must not only calculate (1) what percentage of all earthquakes were preceded by volcanic activity within the five year period, but also, (2) what percentage of all volcanic activity was followed by earthquakes within the 5 year period. With regard to the former, at least 7 of the 9 damaging Central Valley earthquakes (or 78%) were preceded by volcanic activity within a five year period (see dashed lines from upper to middle graph, Figure 20). This is a lower limit because volcano activity might have occurred, but the reports are missing. The percentage could, therefore, be higher if all eruptions were known. With regard to the latter calculation, no more than 8 of 38 volcanic eruptions (or 21%) were followed by a damaging Central Valley earthquake within a five year period. This is an upper limit because volcano reports might be missing; the percentage could, therefore, be lower if all eruptions were known. This statistic only includes eruptions through 1978.

The interpretation we can make, therefore, is that damaging Central Valley earthquakes are more likely to occur during periods following volcanic activity than during periods of volcanic quiescence (in at least 78% of the cases). Volcanic activity on the other hand, is not a very good "predictor" of future earthquakes in Central Valley because no more than 21% of the eruptions are followed by these events.

The record of large earthquakes ($M_s \geq 7.0$) shown at the bottom of Figure 20 seems rather brief for statistical comparisons with volcanic activity. It is interesting that significant volcanic activity has been occurring during the period of seismic quiescence ($M_s \geq 7.0$) from 1953 through 1977. This time period is indicated by the dashed lines from the top graph to the bottom graph in Figure 20. As stated above, earthquakes in Costa Rica which are $M \geq 7.5$ are likely to have originated from the subduction zone; most of the earthquakes $7.0 \leq M_s \leq 7.5$ could also have been subduction zone sources, but we will not be certain until our synthetic seismogram modeling is complete. Volcanic activity has been associated with large subduction zone earthquakes in Japan.[26] The information for Costa Rica is, as yet, too sparse for us to draw any similar conclusions however.

B) Earthquake Damage and Intensity

Historic earthquakes, which would cause serious damage to the San Jose/Cartago area if they were ever to be repeated, have been summarized above and preliminary isoseismal maps that were prepared for five of these earthquakes can be found in Appendix H. The intensity ratings shown on these four maps are based on the Modified Mercalli Scale. (See Appendix I.) To some extent this is a judgement because reporting and population density are reduced with increasing time back into the past. Future results of work in progress may refine the information presented here.

Figure 21 shows the range of intensity and the aftershock area for damaging earthquakes in Costa Rica between 1822 and 1983. Figure 22 is a Costa Rica damage estimate map of future earthquakes based on the historic earthquake intensity data and a composite image of the isoseismal maps. The latter figure indicates three potential regions for damages at the intensity of VII, VIII, and IX. Each of these intensities has specific damage estimates[27]:

VII. Difficult to stand. Noticed by drivers of motor cars. Hanging objects quiver. Furniture broken. Damage to masonry D,[28] including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices (also unbraced parapets and architectural ornaments-CFR). Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slides and caving in also on sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged.

VIII. Steering of motor cars affected. Damage to masonry C; partial collapse. Some damage to masonry B; none to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.

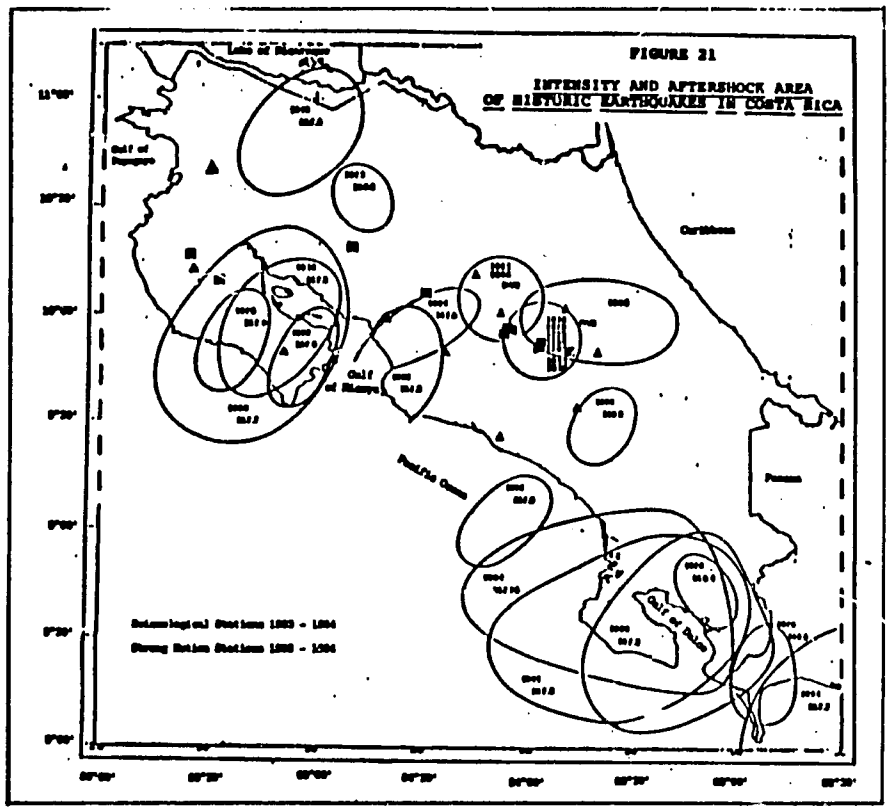


FIGURE 21

INTENSITY AND AFTERSHOCK AREA OF HISTORIC EARTHQUAKES IN COSTA RICA

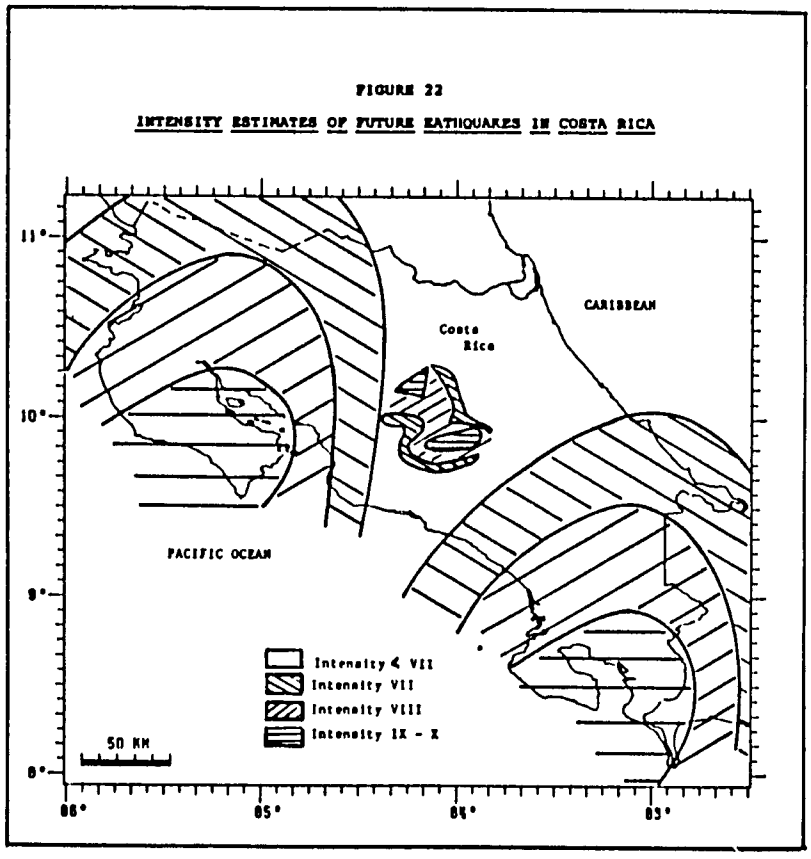


FIGURE 22

INTENSITY ESTIMATES OF FUTURE EATHQUAKES IN COSTA RICA

IX. General panic. Masonry D destroyed; masonry C heavily damaged, sometimes with complete collapse; masonry B seriously damaged. (General damage to foundations--CFR.) Frame structures, if not bolted, shifted off foundations. Frames racked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alleviated areas sand and mud ejected, earthquake fountains, sand craters.

X. Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rail bent slightly.[29]

There are three regions most likely to experience damaging earthquake intensities in the range VII - IX based on historic earthquake patterns. The Nicoya Peninsula, the Osa Peninsula and Burica Point, and the Central Valley are likely to experience intensities of IX. Moving from the coast inland at the Nicoya and Osa Peninsulas the intensity will be reduced to VIII and eventually VII. In the central part of the country, areas to the southeast and northwest of the Central Valley will experience intensities of IX, while the Central Valley itself, where the capital is, will feel lesser intensities from future earthquakes, more likely an intensity of VIII or VII.

C. Earthquake Seismicity and Tectonics

The purpose of this part of the Project is to show new evidence for subduction along the southeastern terminus of the Middle America Trench, where the Caribbean Plate and two other plates, the Pacific Plate and the Nazzca Plate intersect. Most studies of the Middle American trench have occurred along the northwestern section of the trench, off Mexico. (Refer back to Figure 16.) This project has initiated research looking at the southeastern part of the trench.

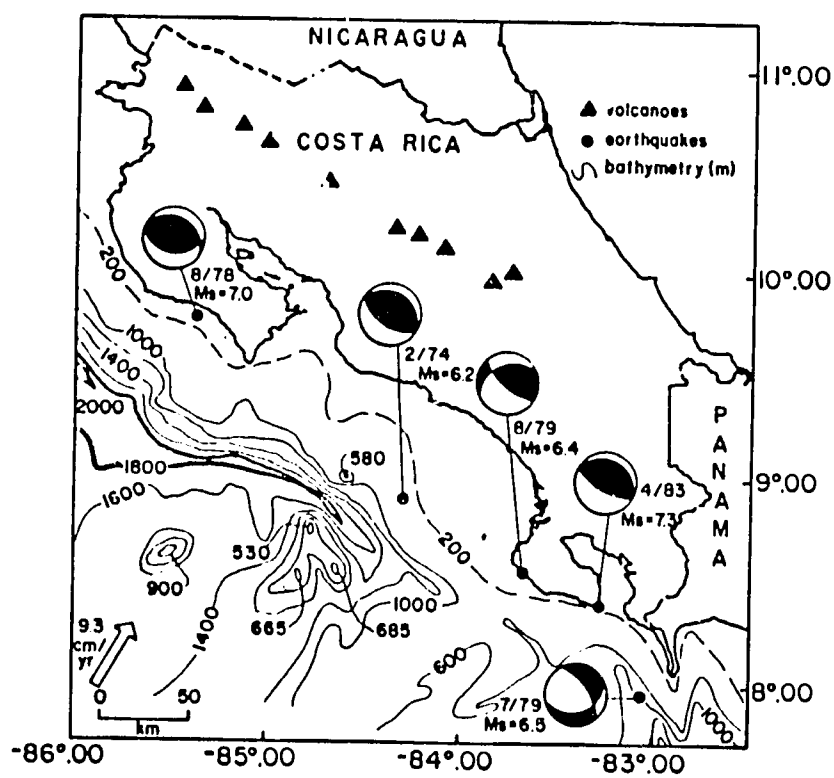
The trench itself does not show in the bathymetry of the ocean floor off southeast Costa Rica, but work done by Project staff indicate that although no topographic

expression for the trench is found in southeast Costa Rica, subduction zone earthquakes have recently occurred in this region. The trench itself does not show in the bathymetry, mainly because the Cocos Ridge fills the trench, covering its existence in this area. (Refer back to Figure 17.) An important finding of this Project is the seismic subduction of the Cocos Ridge. Historically, in other regions of the world where aseismic ridges (quiescently built ridges) have formed and are subducted, they have done so aseismically. The Cocos Ridge on the other hand is an anomaly to these findings, as the ridge, also an aseismic ridge, is colliding and subducting under the Caribbean Plate seismically.

Large seismic events have occurred in the northwestern and southeastern part of the country. No large earthquakes have occurred in the central region of the country however and, therefore, this region has been identified as a seismic gap by several authors.[30]

FIGURE 23

FIVE MAJOR EARTHQUAKE EVENTS SINCE 1974



The occurrence of five large earthquakes recorded world wide and new data from seismograph stations recently installed in Costa Rica has provided a good opportunity for detailed studies regarding mechanisms for subduction along the termination of the southern end of the Middle America Trench. Figure 23 shows the seismicity of the most recent and largest events which have taken place since 1974. These are also the largest events which have occurred in Costa Rica since 1952.

Waveform modeling of the two events that took place in 1979 (M_s=6.5 and M_s=6.4) indicate high angle normal and reverse faulting within the upper Caribbean plate. (See Appendix J for the detailed body waveform model of all five earthquakes used to make this analysis.) Depths constrained by waveform modeling and relocation place these two events at 10 km and 9 km, respectively, well above the subduction interface contact where the other three events are located (between 17km - 23km).

Body waveform modeling for the three other large earthquakes, one in 1974 (M_s=6.2), another in 1978 (M_s=7.0), and the last in 1983 (M_s=7.3) and waveform comparisons for a M_s=7.5 earthquake in 1941, indicate shallow underthrusting of the Cocos Plate beneath the Caribbean Plate as far south as the trench abutment with the Panama Fracture Zone. This is also the location where the seafloor expression of the Cocos Ridge intersects the Middle America Trench.

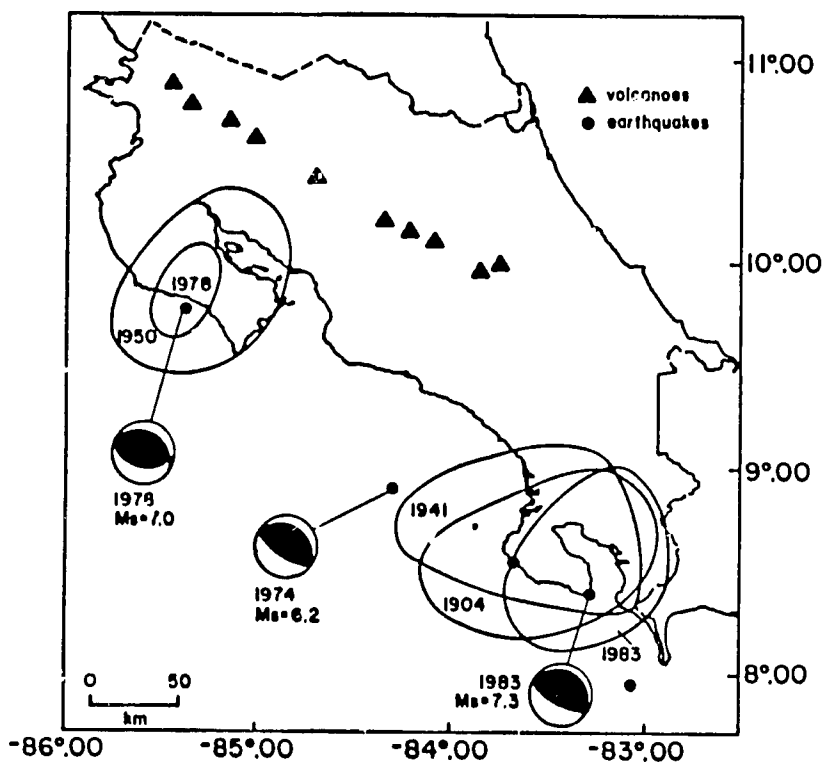
Figure 24 shows aftershock areas for some of the older, as well as the three recent subduction earthquakes. It should be noted that this figure indicates that recent earthquakes have ruptured the same areas where older events have taken place. The 1978 event is in close proximity to a 1950 earthquake. (There was also a 1916 event in this same region which is not shown in this figure.) The most recent 1983 event is located in the vicinity of two previous earthquakes, one in 1904 and the other 1941.

The 1974 earthquake (M_s=6.2) in the central region did not release the energy that has been stored since 1952, when the last major earthquake (M_s=7.3) took place in this location. This region could rupture with an earthquake M_s=7.5 to release this stored seismic energy. A second hypothesis may be that the central region is subducting aseismically, that is, it is slipping without friction between the two plates and therefore is not able to store energy. As more stations are brought into operation in

Costa Rica, a clearer understanding of the stresses involved in this region will be brought to bear on whether the region cannot store energy (and why), or if it is storing energy to be released as a large event in the future.

FIGURE 24

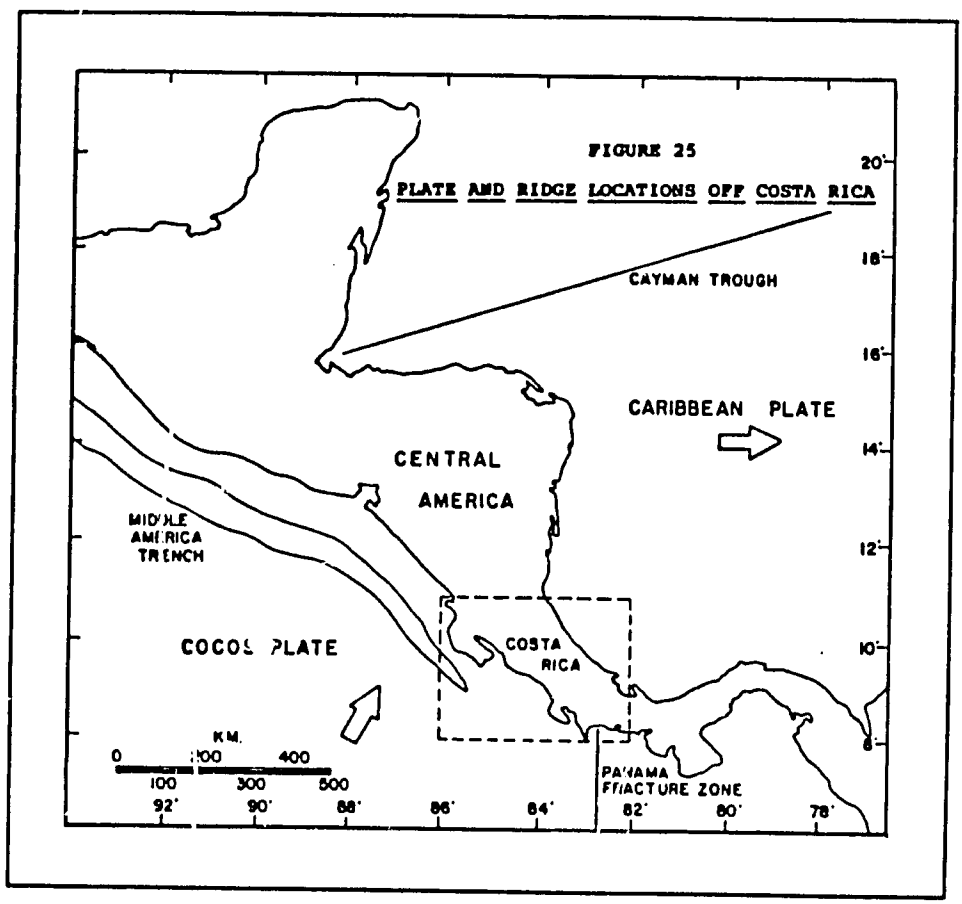
THREE MAJOR SUBDUCTION EVENTS SINCE 1974



The largest subduction events in the country have occurred in the southern part of Costa Rica where the Cocos Ridge is intersecting the trench and being subducted under the Caribbean Plate. This ridge is the trace of a hot spot, where the hotter temperature of the crust on the Cocos Ridge here provides greater buoyancy and, therefore, an increased resistance to subduction as compared with the adjacent region to the northwest, where the plate is much cooler.

Additionally, the subduction of the Cocos Ridge in southern part of the country coincides with the termination of the volcanic chain in Costa Rica, a phenomena that has been observed in other areas of the world where oceanic ridges have collided with continental plates. This region

is also a unique tectonic setting with the Cocos Ridge intersecting not only the trench but a triple plate junction. It is a possibility to consider that the Panama Fracture Zone between the Cocos and Nazzca plates has moved northward to the present location in order to accommodate the stresses produced by the subduction of the Cocos Ridge. (See Figure 25.)



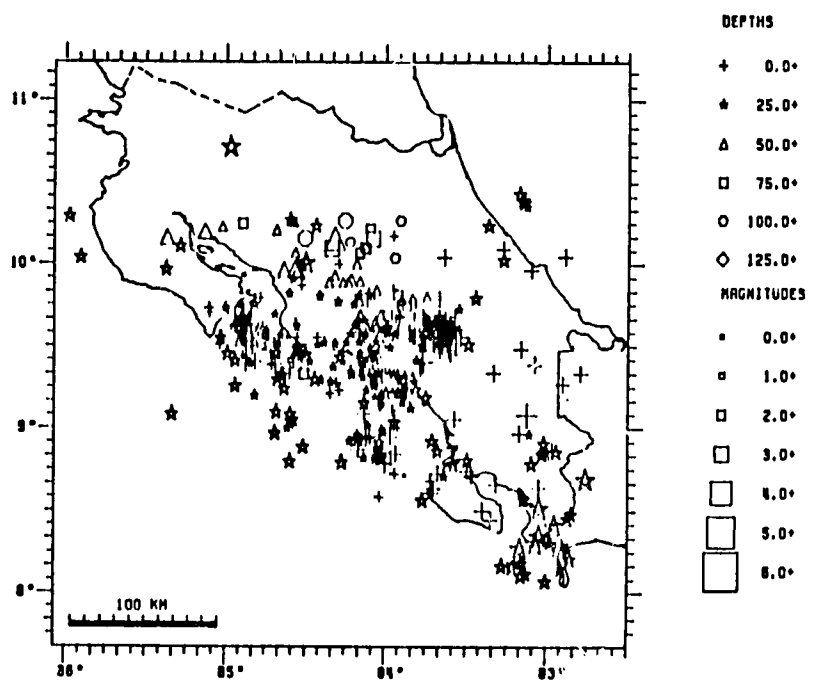
In the central region of Costa Rica, this plate collision produces moderate earthquakes which appear to define a well developed Benioff Zone (subduction zone) dipping at about a shallow 20° angle. The Cocos Plate converges with the Caribbean plate under Costa Rica at an angle of 30° northeast. Further northwest, body waveform modeling for a large earthquake in 1978 (M_s=7.0) and data from the new seismographic stations indicate shallow subduction similar to that found to the southeast, near Panama.

As the Cocos Plate subducts under the continent coincidental to the rising of the volcanic chain on the surface, seismograph station data also locate a more steeply dipping (about 35° to 40°) continuation of the shallower (20°) subduction zone found off the coast of Costa Rica. Preliminary results, (shown in Figures 36 and 37 in Appendix J), indicate simple source rupture mechanisms for the recent earthquakes in northwestern and central Costa Rica and evidence for complex rupture in the southeast, near the termination of the subduction zone along the Cocos Plate.

Figure 26 shows the map locations of all earthquakes of local magnitude $4.5 \geq M_L \geq 2.0$ that occurred in Costa Rica between April-December, 1984.

FIGURE 26

EARTHQUAKES IN COSTA RICA, APRIL - DECEMBER, 1984

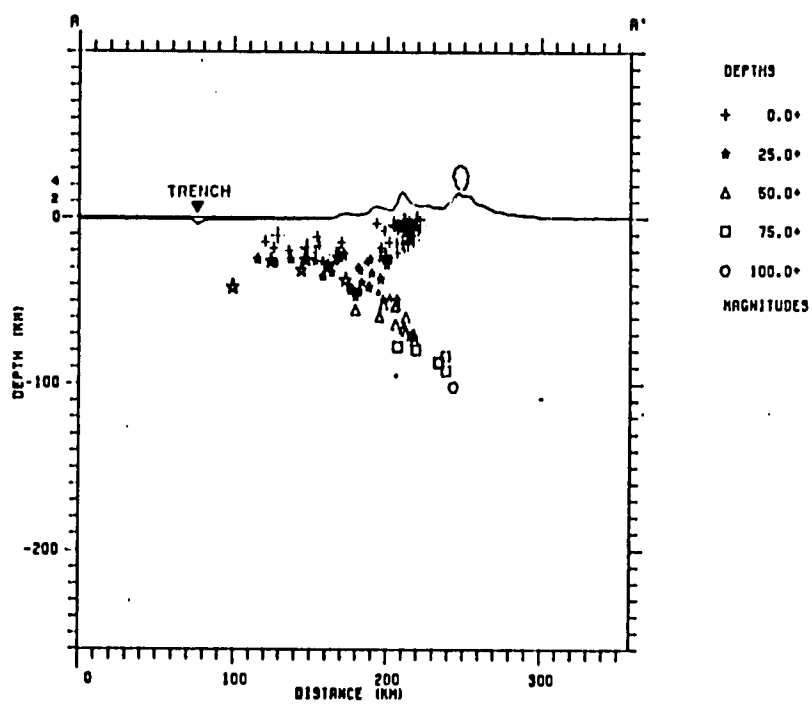


Clusters of events can be seen in the regions where the two large earthquakes of 1983 (M_s=7.3 and M_s=6.3) occurred. This figure indicates there is a relative

homogeneous seismicity occurring offshore of central and southeastern Costa Rica, whereas very little seismicity has taken place in the northwestern part of the country.

FIGURE 27

CROSS-SECTION OF EARTHQUAKES IN COSTA RICA, APRIL - DECEMBER, 1984, SHOWING SUBDUCTION



A projection of the observed seismicity, for the same period of time, with depth is shown as a cross-section in Figure 27. Only the best quality data has been used in this figure, in which a well defined Benioff Zone can be traced to a depth of a 110 kilometers. This new evidence, together with the analyzed waveform modelling of the recent large earthquakes indicate that subduction of the Cocos Ridge underneath the Caribbean plate is continuous and well defined all the way down to the abutment with the Panama Fracture Zone.

D) Seismology Summary

Three main bodies of data, earthquake potential, earthquake damage and intensity, and seismic and tectonic activity, were reviewed in the study of seismicity in Costa Rica. A heavy concentration was placed on the Central Valley region throughout this study because of its locus as a population center.

The earthquake potential analysis concerned four types of earthquake data: The potential for earthquakes and damage from shallow surface faults in the Central Valley; the potential for large earthquakes originating from the subduction zone of Central Costa Rica; the potential for large earthquakes from an unknown source; and phenomena preceding large damaging earthquakes in the short to intermediate time frames.

Though the specific shallow surface faults in the Central Valley that would potentially produce damage are unknown, seismic activity in the central region of Costa Rica poses a large threat because it is the population center of the country. Based on historic earthquake data now available, it is calculated that there is a 30 percent probability of an earthquake event (approximately $M_s = 6.5$) in the next three years from shallow surface faulting in this region.

There are two hypotheses concerning earthquakes originating from the subduction zone of Central Costa Rica. According to McCann and other authors a possible outcome of subduction is that there is a fifty percent chance of rupture in this region in the future. Project research indicates subduction zone earthquakes are produced throughout the entire trench length of Costa Rica. They also suggest another hypothesis with regard to subduction of the central region: that the area is subducting aseismically without producing earthquakes. Reserchers would thus conclude that all previous earthquakes in the central region are a response to shallow surface faulting and not subduction for the time history analyzed.

Seismic release in the central zone has been significantly less between 1900-1983 then in the northwest and southeast zones. Project findings indicate that the period from 1904-1952, with the higher rate of earthquakes, is the 'normal' background rate. They further suggest that a large earthquake of $M_s \geq 7.5$ should be expected, and is likely to come from the subduction zone under Costa Rica. The damage potential of such an earthquake is unknown.

Other phenomena preceding large damaging earthquakes in Costa Rica have been analyzed for short to intermediate time periods: 1) Known data regarding foreshock sequences worldwide were gathered. Costa Rica evidences similar envelopes, in the shallow seismic activity with drops following the peak rate of the foreshock sequence prior to the mainshock. This is characteristic of examples found worldwide. 2) At the present, seismicity in the Central Valley region suggests a slow stress build up pattern which might be associated with a repeat of a Central Valley event on shallow surface faults and similar to the historic events in 1841, 1851, 1888, and 1910. 3) Damaging Central Valley earthquakes were found to be more likely to occur after periods of volcanic activity rather then periods of volcanic quiescence. Volcanic activity on the other hand was not a good predictor of future earthquakes in the Central Valley.

Earthquakes in Costa Rica $M_s \geq 7.5$ are likely to have originated from the subduction zone. Project research indicates that most earthquakes on the order of M = 7.0 - 7.5 might also be from subduction sources. This hypothesis may be confirmed when the synthetic seismogram modeling is complete.

The second major area in the seismicity study was the earthquake damage analysis, based on historic earthquake intensity data and isoseismal maps, which indicated that three regions are most likely to experience seriously damaging earthquakes at the intensity of VII, VIII, and IX. The three areas likely to experience maximum intensities are the Nicoya Peninsula, the Osa Peninsula and Burica Point, and the Central Valley.

The final part of the seismological research conducted by Project members supports new evidence for subduction along the southeastern terminus of the Middle America Trench. Most studies to date have reviewed the northwestern section of the trench, off Mexico, rather then the southeastern section of the Middle America Trench which is believed by Project staff to extend all the way to the abutment of the Panama Fracture Zone off southeastern Costa Rica.

An important finding of this research is the seismic subduction of the Cocos Ridge. Historically, in other regions of the world where aseismic ridges have formed and are subducted, seismicity is greatly reduced especially the large earthquakes. The Cocos Ridge on the other hand is an anomaly to these findings. Subduction research of the Cocos

Plate under the Caribbean shows that recent earthquakes have ruptured in the same areas where older events have taken place. Synthetic waveform modeling, indicates that the subduction process occurs along the entire length of Costa Rica, right up to the Panama Fracture Zone. Recorded earthquakes define a maximum depth for the subduction zone (Benioff) of 120 km. under central Costa Rica. The shape or angle of the subduction is relatively shallow and resembles the somewhat shallow dipping zones that are found in Alaska or Mexico.

IV. CONCLUSION

Major developments toward the Project's primary objective, the establishment of a permanent national seismograph network in Costa Rica, occurred during the two years UCSC participated in this joint project with the Agency for International Development and the Government of Costa Rica, from October 1982 - September 1984. Five major efforts were simultaneously directed to fulfill this primary objective and included, training local personnel in Costa Rica in the establishment, operation, and maintenance procedures of the seismograph network, developing scientific expertise in Costa Rica to process and analyze incoming data, initiating an earthquake preparedness project and conducting earthquake response planning with the government, providing technical assistance in energy development, mineral exploration, and hazard reduction analysis, and lastly, offering short-term traineeships and scholarships in the United States for Costa Rican individuals.(31)

Effort 1 saw to it that essential equipment was purchased and installed. The major items that were bought include 20 strong motion accelerographs, 10 of which have been installed and are fully operational; 15 seismograph stations of which 11 are installed and are fully operational; four portable seismograph units; a standby power generator; three micro computers and related software; and age dating laboratory equipment (four Tennelec TC256 alpha spectrometers and one 2000-channel analyzer). Refer to Appendix A for a complete list of equipment purchases.

Parallel to the equipment purchase efforts, expertise has been developed for data collection and analysis, routine and emergency reporting procedures, and multi-group participation from the neighborhood to the national level (Effort 2). Training in Costa Rica covered network installation, maintenance, equipment testing and checking, and troubleshooting techniques. Highly specific training was provided to a few individuals in the fields of electronics, computer programming, and data analysis. Data reduction programs were established for earthquake locations and catalogues of this data are currently produced monthly in Costa Rica and at UCSC.

Potential hazards to the major population centers of Costa Rica have been identified in Effort 3 through several approaches: Geological reconnaissance, volcanological research, synthetic accelerogram modelling, and analysis of the seismic history, damage and intensity potential and tectonic framework of earthquakes.

Geological reconnaisance was completed in some areas of the country to check the accuracy of a country-wide fault map that was developed using existing maps and aerial photographs. Two main active surface fault systems in Costa Rica, one in the Coastal Range and a second in the Talamanca Range were identified. Faults in the Talamanca Range are small with a variety of structural trends.

Geologic evidence was not found to support the "Cartago Fault" theory of damage. In fact, the reconnaissance work of 1984 indicates that prediction of earthquakes based on fault data will be difficult because of the number of smaller faults. New tools for the study of these small faulting systems, rather than the current methodologies which are utilized for large fault mechanisms, should continue to be developed.

Four of the major volcanoes in Costa Rica are monitored regularly using dry tilt arrays, seismometers, chemical analysis of samples, and radiocarbon age dating techniques. Poas and Irazu are the quietest of the four volcanoes studied, followed by Turrialba and then Arenal. A lab for microscope study of volcanic rocks in thin sections was developed at UNA while a counterpart for radiometric dating has been established at UCSC and seven preliminary measurements of Costa Rican lavas have been made.

Geophysical and geochemical monitoring have been the main emphasis of the volcanology research segment of this project. Survey and tilt networks are established on Irazu, Poas, Arenal, and Turrialba. While temperature and chemical analysis occur at all four stations, seismograph stations have been installed at Irazu and Poas and Rincon de la Vieja. The recent eruption at Arenal has been analyzed and though small volcanic crises may occur before the eruption terminates, Arenal is unlikely to approach the explosivity it had in 1968 because its magmas are being effectively degassed.

To bring new data on Turrialba closer into line with information available on Irazu and Poas the geology of Volcan Turrialba has been mapped and volcanic samples have been chemically analyzed. Silicon dioxide, the most fundamental element analyzed, has decreased with time and future eruptions are likely to be similar to that of Irazu in 1964. The potential for a debris avalanche at Turrialba is still a possibility no matter what the silicon dioxide content of the eruptive material, most likely ash fall and lavas.

Strong ground motion mechanisms and local building response to moderate earthquakes are being monitored. Theoretical synthetic accelerograms have been developed using computer programs to model groundshaking intensities. This is a positive move toward the development of quantitative measurements from strong motion damage and the creation of necessary building applications, based on this knowledge, so that preparation for the adequate protection of people and structures in Costa Rica can occur.

Earthquake potential, earthquake damage and intensity, and seismic and tectonic activity were reviewed in the study of seismicity in Costa Rica. Seismic activity in the central region of Costa Rica poses a large threat because it is the population center of the country. There is a thirty percent probability of an earthquake event in the next three years from shallow surface faulting in this region.

Historical seismicity patterns are indicative of a high seismic potential for Costa Rica today. Measures toward earthquake preparedness should include planning for two potential earthquakes: (1) a moderate sized but highly damaging shallow earthquake in the Central Valley region and (2) a large ($M_s \geq 7.5$) earthquake along the subduction zone, which might cause serious damage, but could be less disruptive to the San Jose/Cartago area than a Central Valley earthquake.

Project research indicates subduction zone earthquakes are produced throughout the entire length of Costa Rica. This research also suggests a new hypothesis with regard to subduction of the central region: that the area is subducting aseismically without producing earthquakes and that all previous earthquakes in the central region are a response to shallow surface faulting and not subduction thereby creating a seismic gap along this portion of the coast.

There is potential for an earthquake in the central region of Costa Rica at a $M_s = 7.5$ to release seismic energy. Project staff recognize this potential, but are continuing to research the hypothesis that the central region is subducting aseismically and, therefore, is unable to store energy. As more stations are brought into operation in Costa rica, a clearer understanding of the stresses involved in this region will be brought to bear on whether the region is unable to store energy and why, or if the region is storing energy that is likely to be released as a large event in the future. It is a possibility to consider the Panama Fracture Zone between the Cocos and Nazzca plates has moved northward to the present location in order to accommodate the stresses produced by the subduction of the Cocos Ridge. The data further suggest that a large earthquake of $M_s \geq 7.5$ should be expected, and is likely to come from the subduction zone under Costa Rica. The damage potential of such an earthquake is unknown.

Seismological research conducted by Project members supports new evidence for the subduction along the southeastern terminus of the Middle America Trench which is believed to extend all the way to the abutment of the Panama Fracture Zone off southeastern Costa Rica. An important finding of this research is the seismic subduction of the Cocos Ridge. Historically, where quiescently built ridges, such as the Cocos, have formed and are subducted, they have done so aseismically. The Cocos Ridge is an anomaly to these findings, as this aseismic ridge is colliding and subducting under the Caribbean Plate seismically.

Costa Rica evidences an envelop, or drop in seismic activity following the peak rate of the foreshock sequence prior to a mainshock during an event which is characteristic of examples worldwide. During a review of other phenomena which included research on events that precede large damaging earthquakes in Costa Rica, it was found that Central Valley earthquakes are more likely to occur after periods of volcanic activity rather then periods of volcanic quiescence.

In support of Effort 3 over a hundred talks were given by Costa Ricans during the past two years to neighborhood and community level groups in order to foster the earthquake preparedness and response planning project with the Government of Costa Rica.

Technical assistance in energy development, mineral exploration, and hazard reduction analysis has been provided to meet the needs expressed in Effort 4, and all of the information developed by this project is publicly available. RECOPE has confirmed the Projects' assistance with oil exploration. A seminar on Costa Rican geology and its relation to the potential location of oil was given in Costa Rica by UCSC Professor Eli Silver. F. Guendel's work on plate subduction is also informative about the location of minerals in Costa Rica.

Effort 5 has been concerned with short-term traineeships and scholarships which have been provided to several Costa Ricans (e.g. the two Costa Rican students currently in residence at UCSC completing Ph.D. programs at the Charles F. Richter lab in seismology and volcanology). Conferences and workshops were attended by a dozen Costa Ricans in order for them to receive practical technical expertise for equipment operation, learn to perform data analysis, be aware of theoretical developments in related fields, and to participate in discussions on international cooperation and assistance in the event of a crisis.

V. FOOTNOTES

1. USGS has reviewed our data and confirmed our findings for the occurrence of such an earthquake.

2. Five separate projects are being simultaneously conducted under this grant, and because the work is at an accelerated pace due to potential earthquake hazard, each activity described in the following pages is budgeted for minimum monies, with virtually no allowance for cost increases due to salary rate increases or equipment price increases. The is cost effective for the work that will be produced in that investments are coordinated to provide efficiency and overlapping benefit. To date, all work is on schedule, with only minor differences and adjustments for the planned completion date.

3. From: "Memorandum of understanding between the Agency for International Development (AID), the National University (UNA), and the University of California in order to install the strong motion component of a permanent national seismographic network in Costa Rica, and to establish an earthquake hazard reduction program." October 31, 1984.

4. The services of the Division of Mines and Geology of the State of California have been donated without charge to this Project.

5. This has been discussed with Paul Bell and will be developed further as efforts progress.

6. This work plan is being coordinated with the Office of Federal Disaster Assistance (OFDA) and Paul Bell.

7. Installation is pending funding during FY85 for site development and equipment to transmit and record data.

8. The visit to Hawaii coincided with the celebration of the workshop on "Pacific Volcanology: Forecasting Eruptions", where state of the art volcano forecasting was discussed and different eruptive behaviors were contrasted. A UNESCO technical meeting on "International Mobile Early Warning Systems for Volcanic Eruptions and Seismic Activities" and "Training and Research in Volcanology in the Western Pacific Region" was held after the workshop. These two projects of UNESCO, now under their final review format, offer great perspectives for international cooperation and assistance in case of volcanic crisis, as well as on the job training for many volcanologists around the world. Twelve scientists reviewed the project for UNESCO during this session, including E. Malavassi representing the Latin American countries.

9. This thrust belt may be presently active and field work by scientists at Lamont-Doherty is underway on land. UCSC has been funded by the National Science Foundation to carry out a marine geophysical study of the North Panama thrust belt, beginning in March, 1985. We expect to have significant input to this problem by the summer of 1985 as a result of this work.

10. A detailed account of this work and an expanded overview of its regional tectonic significance is presented in Charles E. Heywood thesis, "Forearc Deformation Related to Collision of the Cocos Ridge, Costa Rica, Central America", Earth Sciences Department, University of California, Santa Cruz.

11. Woodward-Clyde, Personal Communication.

12. Charles E. Heywood thesis, "Forearc Deformation Related to Collision of the Cocos Ridge, Costa Rica, Central America", Earth Sciences Department, University of California, Santa Cruz.

13. Mr. Aguilar was included as a consultant on this project and was provided some funding toward completion of his field work.

14. It is particularly significant that the 1863-1865 eruption was of dense basalt. If a large body of less dense, more silicious magma had resided under Turrialba before 1863, the 1863-1865 magma would have ponded at its base due to its higher density. Eruption, then, would have occurred only after a long period of time while the magmas became equal in composition and density.

    Mineral textures and chemistries of the 1863-1865 lavas, however, can only accommodate a maximum of a few percent of in mixed silicious magma. This suggests that a large silicious magma body did not reside in the crust under Turrialba before 1863. It also suggests that a large silicious magma body is not present today, (120 years is probably not sufficient to produce such a body).

15. Jim Dewey, pers. comm; Montero and Dewey (1982); Carr and Stoiber (1977).

16. The probability reaches a value of nearly 60% for the Central Valley during the same time period (10 years) as required for the calculation for the San Andreas fault to reach 7.3%.

17. McCann et. al. (1979)

18. From McCann, et. al., and taken after the bathymetry of Lonsdale and Klitgord (1978).

19. Using standard relations between earthquake magnitude (M_s) and seismic moment (M_o) (see, eg. McNally and Minster, 1981), the observed range of M_s=7.0-7.3 events (open squares in Figure 18) corresponds to seismic moment release of M =0.316 x 10^{27} to 0.891 x 10^{27}, whereas the observed range of M_s=7.5-7.7 is equivalent to M_o=1.778 x 10^{27} to 3.548 x 10^{27}. Thus it can be seen in Figure 18 that seismic moment release within the central zone from 1900 to 1983 has been significantly less than that in the N-W and S-E zones. It is also apparent that seismic moment release has been significantly reduced since 1953, relative to the time period 1904 to 1952, along the entire length of Costa Rica.

20. It is interesting to note that the Western U.S. also experienced a period of relative seismic quiescence during the years 1956-1978

21. Kasahara (1981)

22. We reiterate that this is a report on work which is not yet completed.

23. The most relevant studies for comparison are those by Mogi (1981) and Kanamori (1972), which show increased earthquake swarms and seismicity inland from and prior to large subduction zone earthquakes.

24. Kanamori, 1972

25. Data compiled for Figure 20 are from C. Gonzalez, 1910, "Temblores Teremotos...", Gutemberg and Richter, 1965, "Seismicity of the Earth", Smithsonian Institution, 1981, "Volcanoes of the World."

    with the most reliance on Simkin et al, 1981, for volcanic activity.

26. Kanamori, (1972).

27. The information presently available is not sufficient to distinguish IX and X for Costa Rica.

28. Masonry A, B, C, D. To avoid ambiguity of language, the quality of masonry, brick or otherwise, is specified by the following lettering (which has no connection with the conventional Class A, B, C construction).

> Masonry A. Good workmanship, mortar and design; reinforced, especially laterally, and bound together by using steel, concrete, etc.; designed to resist lateral forces.
> Masonry B. Ordinary workmanship and mortar; reinforced, but not designed in detail to resist lateral forces.
> Masonry C. Good workmanship and mortar; no extreme weaknesses like failing to tie in at corners, but neither reinforced nor designed against horizontal forces.
> Masonry D. Weak materials, such as adobe; poor mortar; low standards of workmanship; weak horizontally.

29. Richter, Mercalli Scale (See Appendix I).

30. Kelleher et al (1973), McCann et al (1979)

31. Project expenses for 1983 and 1984 combined totalled $800,000.

VI. PROJECT RELATED PUBLICATIONS, REPORTS, AND ABSTRACTS

Publications

Gill, Jim, Mark Reagan, and R. Williams, "Open-System Differentiation During or Just Before Historic Eruption of Volcanoes: Arenal, Merapi, Galunggung", in: Proceedings of a Conference on Open Magmatic Systems, Southern Methodist University, 1984. Pg. 56-58.

McNally, K. C., 1982, "Variations in seismicity as a fundamental tool in earthquake prediction," Seismol. Soc. Am. Bull., v. 72, n. 6B, p. S351-S366.

Observatorio Vulcanologico y Sismologico de Costa Rica, Universidad Nacional, Herdia, Costa Rica, Boletin Sismologico Preliminar, April, 1984.

Observatorio Vulcanologico y Sismologico de Costa Rica, Universidad Nacional, Herdia, Costa Rica, Boletin Sismologico Preliminar, May, 1984.

Observatorio Vulcanologico y Sismologico de Costa Rica, Universidad Nacional, Herdia, Costa Rica, Boletin Sismologico Preliminar, June, 1984.

Observatorio Vulcanologico y Sismologico de Costa Rica, Universidad Nacional, Herdia, Costa Rica, Boletin Sismologico Preliminar, July, 1984.

Observatorio Vulcanologico y Sismologico de Costa Rica, Universidad Nacional, Herdia, Costa Rica, Boletin Sismologico Preliminar, August, 1984.

Observatorio Vulcanologico y Sismologico de Costa Rica, Universidad Nacional, Herdia, Costa Rica, Boletin Sismologico Preliminar, September, 1984.

Observatorio Vulcanologico y Sismologico de Costa Rica, Universidad Nacional, Herdia, Costa Rica, Boletin Sismologico Preliminar, October, 1984.

Observatorio Vulcanologico y Sismologico de Costa Rica, Universidad Nacional, Herdia, Costa Rica, Boletin Sismologico Preliminar, November, 1984.

Observatorio Vulcanologico y Sismologico de Costa Rica, Universidad Nacional, Herdia, Costa Rica, Boletin Sismologico Preliminar, December, 1984.

Reports

Guendel, F. and K.C. McNally, 4 October, 1984, "Earthquake and Damage Potential in Costa Rica: A Status Report Based on Work in Progress", Report to U.S. Agency for International Development.

Abstracts

Alfaro, R., et. al., 1984, "Lluvio Acida de Origen Volcanico en Costa Rica", Submitted to: Italian-Latin American Symposium on Volcanic and Seismic Risk, Costa Rica, March, 1985.

Barquero J., et. al., 1984, "Vigilancio Activa: UNA Herramiento en la Reduccion y Evaluacion de Peligros Volcanicos", Submitted to: Italian-Latin American Symposium on Volcanic and Seismic Risk, Costa Rica, March, 1985.

Guendel, F. and K. C. McNally, 4 October, 1984, "Earthquake and Damage Potential in Costa Rica: A Status Report Based on Work in Progress", AGU in press.

Guendel, F. and K. C. McNally, 1984, "Evalucaion del Riesgo Sismico en la Region Central de Costa Rica Borado en la Sismicidad Historica", Submitted to: Italian-Latin American Symposium on Volcanic and Seismic Risk, Costa Rica, March, 1985.

Guendel, F. and K. C. McNally, 1984, "Mecanismos Focales y Sus Implicacioner para el Riego Sismico in Costa Rica", Submitted to: Italian-Latin American Symposium on Volcanic and Seismic Risk, Costa Rica, March, 1985.

Guendel, F. and K. C. McNally, 1982, "The Foreshock-Mainshock-Aftershock Sequence of the 1978 (M_s=7.0) Samara, Costa Rica Earthquake: A Unique Data Set", Earthquake Notes, Seismological Society of America, 53, 81.

Guendel, F. and K. C. McNally, 1981, "Application of the Seismic Gap Method to the Seismicity of Costa Rica, Central America," EOS Trans., AGU, 62, p. 948.

Guendel, F., K. C. McNally, J. Lower, E. Malavassi, and R. Saenz, "New Evidence Regarding Subduction Mechanisms Near the Southern Terminus of the Middle America Trench, Costa Rica, C.A., EOS rans., AGU, in press.

Heywood, Charles E. and Eli A. Silver, "Forearc Deformation Related to Collision of the Cocos Ridge, Costa Rica, Central America, EOS Trans, November, 1983.

Reagan, M. K., and Gill, J. B., 1984, "Open-System Behavior Exhibited by the 1968-present Eruption of Volcan Arenal, Costa Rica," Geological Society of America, Abstracts with Programs, 16, p. 631.

Rojoi, D., et. al., 1984, "Red Sismografica y el Programa de Reduccion de Rissgor en Costa Rica, Submitted to: Italian-Latin American Symposium on Volcanic and Seismic Risk, Costa Rica, March, 1985.

Other

Aguilar, Alvaro D., Jefe Depto. Integracion de Informacion, Refinadora Costarricense de Petroleo, S.A., San Jose, Costa Rica. (B.S. thesis for RECOPE)

Circum-Pacific Volcano Monitoring Seminars held via Satellite, September, October, 1984. (Reporting on and receiving advice on Costa Rican Volcanoes through the World Volcanological Community.)

Heywood, Charles E., "Forearc Deformation in Southern Costa Rica: A Consequence of the Collision of the Aseismic Cocos Ridge", M.S. Thesis in Earth Sciences, University of California, Santa Cruz, December, 1984.

Protti, M., 1984, "Observatorio Vulcanologico y Sismologico de Costa Rica", IPGH: I Jornadadas Geofisicas para C.A. y Caribe, 9-13 Dic., 1984, Panama.

"Volcanic Hazard Studies at Volcan Turrialba Seminar," given to Volcanology and Seismology Group at UNA by Mark Reagan, January, 1985. This included field investigations at Turrialba by seminar participants.

VII. AGENCIES AND INDIVIDUALS CONTACTED

Agency/Individual	Regarding
Gary Holzhausen, President Applied Geomechanics	Telemetry of Tiltmeter Data
Norman Banks United States Geological Society Hawaii Volcano Observatory	Technics in Volcano Monitoring
K. Yamashita United States Geological Society Cascade Volcano Observatory	Technics in Volcano Monitoring
T. Cassadaval United States Geological Society Cascade Volcano Observatory	Technics in Volcano Monitoring
D. Miller United States Geological Society Denver, Colorado	Assist in geological hazard assessments at Turrialba and Arenal
David Harlow United States Geological Society	Seismology
Waverly Person United States Geological Society Denver, Colorado	Data exchange and coordination with world-wide USGS seismic network
Bruce Presgrave United States Geological Society Denver, Colorado	
Daniel Dzurisen United States Geological Society Cascades Volcano Observatory Washington	Review of deformation, date set from Costa Rica volcanoes.
Tony Shakal California Department of Mines and Geology Sacramento. CA	Training on SMA1

Agency/Individual	Regarding
Michael D. Garcia University of Hawaii Hawaii	Assistance with micro-probe chemical analysis Volcan Arenal geochemistry
Gerry Simila UC California, Northridge Pasadena, CA.	OAS grant to assist with computer program development. Partial funds UCSC
Witcome, Jim University of Colorado Colorado	Geodetic and gravity work in Costa Rica

VII. APPENDICES

APPENDIX A

EQUIPMENT PURCHASED AND SHIPPED TO COSTA RICA

LIST OF EQUIPMENT BOUGHT ON AID 1982-83
AID GRANT NO. PDC-0000-G-SS-2213-00

Equipment	Date Purchased	Location	Date Shipped
Seismic Network Component:			
2 Single ch. helicorders	10/25/82	Costa Rica	01/25/83
1 Two ch. helicorder	10/25/82	Costa Rica	01/25/83
2 Amplifiers	10/25/82	Costa Rica	01/25/83
3 Oscillators	10/25/82	Costa Rica	01/25/83
1 Field package	10/25/82	Costa Rica	01/25/83
3 Discriminators	10/25/82	Costa Rica	01/25/83
1 Rack mount	10/25/82	Costa Rica	01/25/83
1 Power supply	10/25/82	Costa Rica	01/25/83
3 Consoles	10/25/82	Costa Rica	01/25/83
paper for helicorders	10/25/82	Costa Rica	01/25/83
6 Single ch. helicorders	10/25/82	Costa Rica	01/25/83
2 Amplifiers	10/25/82	Costa Rica	01/25/83
10 Amplifiers	10/25/82	Costa Rica	01/25/83
5 Oscillators	10/25/82	Costa Rica	01/25/83
5 Oscillators	10/25/82	Costa Rica	01/25/83
10 Field packages	10/25/82	Costa Rica	01/25/83
10 Discriminators	10/25/82	Costa Rica	01/25/83
2 Rack Mounts	10/25/82	Costa Rica	01/25/83
2 Power Supply	10/25/82	Costa Rica	01/25/83
1 Extender Module	10/25/82	Costa Rica	01/25/83
paper for helicorders	10/25/82	Costa Rica	01/25/83
1 Airconditioner	10/21/83	Costa Rica	03/16/83
5 Helicorders	12/19/83	Costa Rica	02/20/84
2 Amplifiers	12/19/83	Costa Rica	02/20/84
2 Discriminators	12/19/83	Costa Rica	02/20/84
2 Rack mounts	12/19/83	Costa Rica	02/20/84
2 power supplies	12/19/83	Costa Rica	02/20/84
2 Oscillators	12/19/83	Costa Rica	02/20/84
2 Seismic Amplifiers	12/19/83	Costa Rica	02/20/84
10 Ranger Seismometers	08/29/83	Costa Rica	12/28/83
1 Synchronized Clock	11/03/83	Costa Rica	12/28/83
20 Solar panels	11/02/83	Costa Rica	12/28/83
8 Transmitters	09/19/83	Costa Rica	12/28/83
8 Receivers	09/19/83	Costa Rica	12/28/83
16 Antennas	09/19/83	Costa Rica	12/28/83
1 Oscilloscope	08/25/83	Costa Rica	12/28/83

Equipment	Date Purchased	Location	Date Shipped
Strong Ground Motion Component:			
10 Accelerographs	08/29/83	Costa Rica	12/28/83
10 Time code generators	08/29/83	Costa Rica	12/28/83
10 Film magazines	08/29/83	Costa Rica	12/28/83
15 Recording film	08/29/83	Costa Rica	12/28/83
2 Battery sets	08/29/83	Costa Rica	12/28/83
10 Desiccant bags	08/29/83	Costa Rica	12/28/83
1 Trace alignment kit	08/29/83	Costa Rica	12/28/83
5 Solar cells	08/29/83	Costa Rica	12/28/83
Volcanology Component:			
1 Cut-off machine	10/07/83	Costa Rica	06/07/84
1 Polarizing microscope	10/12/83	Costa Rica	03/01/84
8 Tiltmeters and accessories	11/30/83	Costa Rica	04/02/84
1 Mechanical point counter	10/10/83	Costa Rica	03/01/84
1 VHF transceiver	08/25/83	Costa Rica	04/02/84
1 Power amplifier	09/16/83	Costa Rica	04/02/84
1 Power supply	09/16/83	Costa Rica	04/02/84
1 Antenna	09/16/83	Costa Rica	04/02/84

EQUIPMENT BOUGHT ON AID 1983-84
AID GRANT NO. ASB-0000-G-00-4015-00

Equipment	Date Purchased	Location	Date Shipped
Seismic Network Component:			
6 Helicorders	04/19/84	Costa Rica	06/01/84
2 Amplifiers	04/19/84	Costa Rica	06/01/84
10 Blank panels	04/19/84	Costa Rica	06/01/84
7 Ranger SS-1	04/11/84	Costa Rica	09/18/84
6 Preamplifiers	04/14/84	Costa Rica	06/01/84
6 Oscillators	04/14/84	Costa Rica	06/01/84
5 Field Packs	04/14/84	Costa Rica	06/01/84
8 Pairs radios plus antennas	06/12/84	Costa Rica	10/18/84
6 Discriminators	04/19/84	Costa Rica	06/01/84
3 Power supplies	07/18/84	Costa Rica	06/01/84
7 Equipment mount racks	03/01/84	Costa Rica	06/01/84
6 Solar panels	04/14/84	Costa Rica	09/18/84
5 Regulators	08/28/84	Costa Rica	10/29/84
1 DEC 350 Professional	07/10/84	Costa Rica	01/30/85
1 Power Generator	10/19/84	Vender	
4 MEQ-800's	05/02/84	Costa Rica	09/18/84
1 Function Generator	03/30/84	Costa Rica	04/02/84
1 Apple computer system	08/21/84	Costa Rica	08/24/84
Strong Ground Motion Component:			
10 Accelerographs & TCG-1's	04/11/84	Costa Rica	09/18/84
Accelerographs & TCG-1's			05/15/85
1 Data Retrieval Unit	05/02/84	Costa Rica	06/01/84
1 Seismic Refraction Equip	05/02/84	Costa Rica	10/18/84
Volcanology Component:			
1 Surveying Equipment	06/29/84	Costa Rica	09/18/84
4 Mass Spectrometers	01/25/84	UCSC	
1 Multi channel analyzing system	01/19/84	UCSC	
1 IBM PC computer system	04/05/84	UCSC	
1 Temperature recording eqp.	12/07/83	Costa Rica	04/02/84

APPENDIX B

COSTA RICA PERSONNEL

AGENCY/PERSONNEL	AREA OF INVOLVEMENT
UNIVERSIDAD NACIONAL (UNA):	
Ing. Rodrigo Saenz	Geologist: Seismology
Ing. Rodolfo Van der Laat	Geodesist: Volcanology
Lic. Jorge Barquero	Geographer: Volcanology
B. Sc. Erick Fernandez	Geographer: Volcanology
M. Sc. Federico Guendel	Seismology
M. Sc. Eduardo Malavassi	Volcanology
B. Sc. Victor Gonzalez	Geographer: Computer Technician
B. Sc. Juan Segura	Geographer: Data Processing Tech.
B. Sc. Carlos Montero	Geographer: Data Processing Tech.
Mr. Daniel Rojas	Electronic Technician
Mr. Antonio Mata	Electronic Technician
Ms. Yadira Solis	Secretary
UNIVERSITY OF COSTA RICA (UCR):	
Ing. Rosendo Pujol	M. Sc.
Ing. Maria Laporte	M. Sc.
Mr. Carlos Segura	Electronic Technician
Ing. Ruben Boroscheck	Civil Engineer
Dr. Jorge Gutierrez	Ph. D.

COSTA RICA PERSONNEL (CONT.)

AGENCY/PERSONNEL	AREA OF INVOLVEMENT
(RECOPE):	
Ing. Roberto Dobles	Executive President
Ing. Pedro Afonso	Petroleum Exploration Group
NATIONAL CIVIL DEFENSE:	
M.D. Lenin Saenz	Civil Defense Commisioner
NATIONAL INSURANCE COMPANY	
Lic. Eddy Alvarez	Executive Director

APPENDIX C

TECHNICAL DESCRIPTION OF SEISMOGRAPHIC NETWORK OPERATION IN COSTA RICA, OPERATED BY UNA

A) Laboratory activities for reporting and data processing:

1. Routine bulletins published on a monthly basis with all Costa Rica earthquakes $\geq$ mag. 2.5 located to $\pm$ 5-10 km. This includes seismicity maps, station coordinates and basic data printouts. Magnitudes listed for all events.

2. Seismograms are read daily with all phase arrivals timed and recorded amplitudes and durations measured and recorded.

3. This data is entered and processed on the computer systems; files are organized and stored in a secure environment.

4. In an emergency situation the readings are taken immediately for preliminary locations.

5. A daily report will be put on an automatic phone answering tape with a listed phone number.

6. A special phone will be maintained with an unlisted number for dissemination of information on an emergency basis to the proper authorities.

7. All data including seismograms will be archived in a suitable environment and be publicly available. In order to maintain a secure data base, no original seismograms will be allowed off the premises of the laboratory. Copies will be made and provided by authorized personnel (within reasonable limits) for the cost of duplication.

B) **Array Configuration:**

1. Twenty-three stations for adequate coverage of Costa Rica.

2. Average station spacing for M $\geq$ 2.5 detection threshold. (Increased density in the heavily populated central valley region.) Some areas inaccessible on eastern flanks.

3. All links to Heredia wil be by radio to:

   a) Prevent a system breakdown due to the loss of phone lines in the event of an earthquake; and

   b) provide alternate signal paths in case of isolated problems.

4. Thirty percent station co-location with SMA-1's (strong ground motion instruments). All stations located to $\pm$ 5m, 3D.

5. Array geometry is non-symmetric to avoid non-unique mathematical solutions for earthquake locating.

6. Access and line of sight to stations are constraints on possible site choices.

7. Array aperture is maximized for discriminating between deep and shallow earthquakes.

8. Stations are located on bedrock and away from sources of environmental and cultural noise, where possible.

9. Stations are located on volcanoes, where possible for:

   a) Detailed volcano monitoring, (a dense portable station array will be brought to supplement on volcanoes when needed due to activity noted from monitoring).

   b) Possibility of combined radio transmission of seismic, tilt, and geochemical data to central observatory for monitoring and information correlation (a special telemetry system design is being investigated).

10. Three stations also include horizontal seismometers for shear wave recording for information constraints on determining earthquake depths and locating offshore earthquakes.

C) **System Specifications:**

1. Total system response is 1 - 0.2 seconds (the same as standard Benioff). System standards are of the highest quality for the acquisition of accurate, necessary data. Exotic equipment has purposefully been avoided because it would be almost impossible to maintain and use under these conditions.

   a) Conforms to Worldwide Standard Seismographic Network (WWSSN).

   b) Ties to largest Short Period database.

   c) High noise in Costa Rica predominately above .1 sec. station with simulated.

   d) Three stations with simulated Wood-Anderson response +4 low gain for preliminary local magnitude & S.

   e) Alarm system for M $\geq$ 4.5.

   f) Satellite timing system for central lab.

   g) One central observatory station for special equipment and testing.

   h) Station portable array.

2) **Packaging**

   a) Vaults in the earth provide:

      i) better temperature control; and

      ii) no long lines to minimize high pot during storms.

   b) All electronics in hermetically sealed boxes for protection from:

      i) humidity; and

      ii) acid environment near volcano.

3) Power

a) All power in the field provided by solar panels.

b) Radios in Heredia on solar power.

c) Stand by generator in Heredia for remaining power.

d) Regulated power to all electronics and computers.

e) Small uninterruptable power source for emergency computer.

4) Calibration (all done to exact standards):

a) Each component calibrated individually.

b) Total system calibrated as a unit.

D) **Personnel**

Personnel involved in all phases of the project are using specific criteria (equivalent to the standards of world wide observatories) in establishing an effective and accurate system to monitoring earthquakes and volcanoes in Costa Rica. This includes:

1) Array configuration

2) Installation criteria

3) Electronic electromechanical techniques

4) Calibration and troubleshooting techniques

E) **System maintenance**

1) Adequate modern test equipment will be maintained both for the field and at the Heredia laboratory (e.g., oscilloscopes, meters).

2) An adequate stock of spare parts will be kept in Heredia. This will include two spare stations for immediate replacement of any station which is totally destroyed (e.g., vandalism, theft, severe storm damage).

3) One vehicle and driver will be available 100% time for routine maintenance of the array.

4) A standby timing system will be maintained in case of the loss of satellite time.

5) An adequate stock of spare batteries (six) will be maintained in a fully charged state.

6) All necessary tools (e.g., soldering irons, screw-drivers, etc.) will be kept at the Heredia lab.

F) **Strong Motion Studies to the University of Costa Rica**

1) All instruments are on site recording

   a) No communication necessary

2) Array Configuration

   a) Average spacing 40 km

   b) Optimized source and path information

3) Equipment Specifications

   a) Standard Strong Motion Accelerometer (SMA-1)

   b) Most commonly used instrument in world with standard data processing techniques.

4) Packaging

   a) Free field sites in vaults. (Refer to packaging discussion for seismographic network n preceding section C2.)

5) Site criteria are:

   a) high seismic risk locally,

   b) locations are of social and economic importance;

   c) locations of important structures.

TECHNICAL AND EMERGENCY COMMUNICATION RELATIONSHIP

COMMUNICATION: General Principles

Flow of Information

1. Routine Communications: To Civil Defense

   a. Daily report to civil defense, on earthquakes ≥ 2.5

   b. Abnormal volcanic events (i.e. swarms, increasing temperature, drastic changes in tilt, geochemistry, etc.)

2. Universidad Nacional Emergency Communications: To Civil Defense, University of Costa Rica, and University of California at Santa Cruz,

   Communication between UNA - UCR - Civil Defense by Radio - Allocation of frequency needed.

   Communication UNA - UCR with UCSC by PeaceSat Satellite in case of emergency. Satellite link has been purchased.

   Report on 24 hour basis:

   a. Earthquakes $M \leq 5$ (alarm trigger system) within an hour after the earthquake (including preliminary locations and magnitudes).

   b. Impending volcanic eruptions.

   c. Expected damage scenario from preplan maps produced by the project.

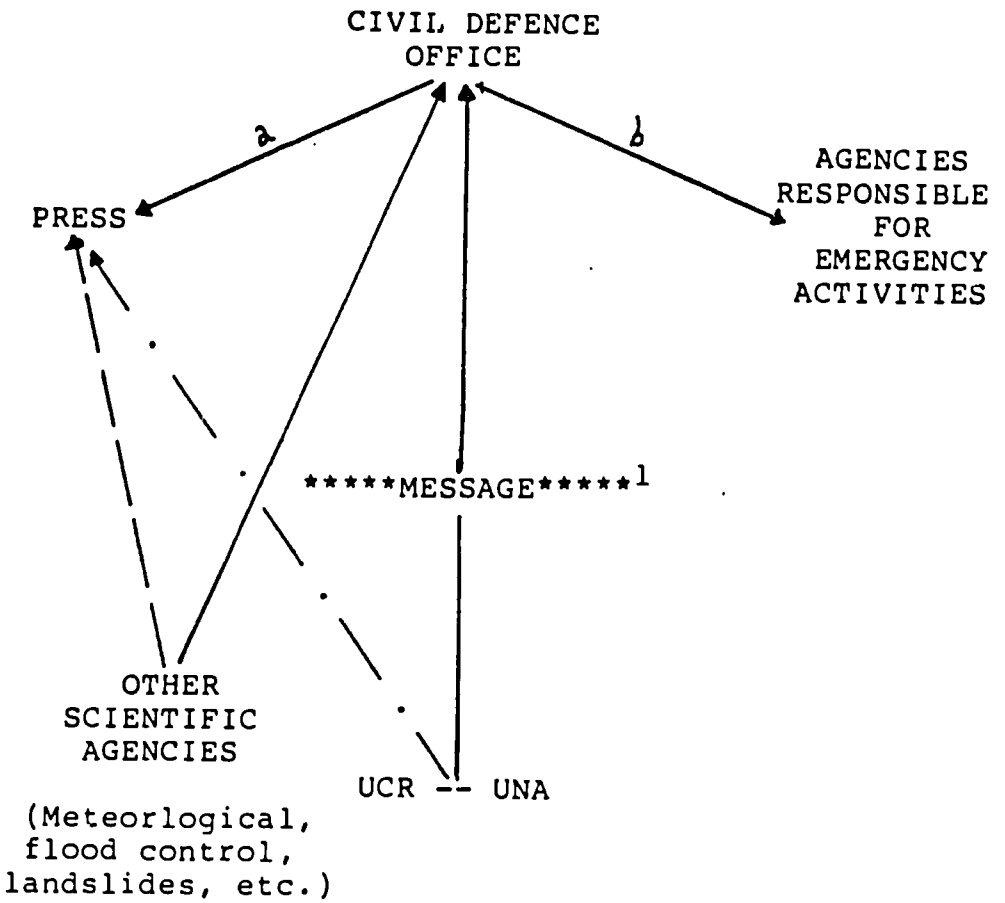
3. UCSC emergency communication to AID, Washington, same as above, from monitor at UCSC, or from UNA/UCR.

4. Special Studies: Risk and hazard assessment, vulnerability for disaster planning (i.e., volcano, earthquakes) specially (lifelines) and life system (hospitals).

FIGURE 28

TYPICAL RELATIONSHIPS BETWEEN TECHNICAL AND EMERGENCY RESPONSE

COMMUNICATION



a Emergency Information to the Public

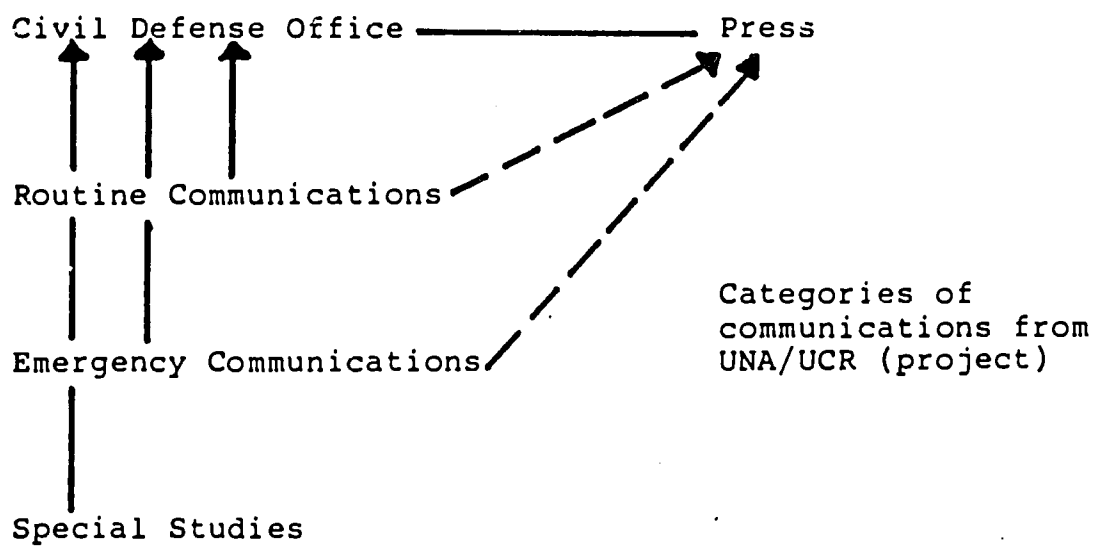
b Emergency Information to Agencies

Press statement giving location, magnitude, and depth.

[1] Message: Earthquake location, magnitude, depth and expected damage based on damage scenario maps produced by the project and given in advance to the civil defense office.

FIGURE 29

TYPES OF COMMUNICATION WITH CIVIL DEFENSE AND PRESS



US/AID/OFDA/UCSC COSTA RICA

Project Organization

Coordinating Institutions:

UNA	-- Volcano monitoring component -- Volcanic hazard -- Seismic network component -- Earthquake hazard
UCR	-- Accelerograph network component -- Seismic vulnerability analysis
Civil Defense	-- Transfer information and experience from California for earthquake preparedness and educational purposes.
UCSC	-- Technical assistance

APPENDIX E

U. S. PERSONNEL TRAVEL LOG

Trip Date	Traveler	Destination	Agency	Contact Person	Tasks Completed
12/19/83-12/26/83	Lawrence Feldman	Costa Rica	Library		Data collection on historical earthquakes
06/21/84-06/30/84	Lawrence Feldman	Nicaragua	Nat. Archive		
07/26/83-09/06/84	Chuck Heywood	Costa Rica	UNA	Eli Silver	Thesis fieldwork
12/11/83-03/12/84	Chuck Heywood	Costa Rica	UNA	Eli Silver	Thesis fieldwork
01/25/84-02/07/84	Haller Igel	Costa Rica	UNA/UCR	John Lower	Work on SMA-1's
07/04/84-07/13/84	Haller Igel	Costa Rica	UNA/UCR	John Lower	Develop budgets
12/19/83-12/26/83	Judith Lelchook	Costa Rica	Nat. Archive	Lawrence Feldman	Thesis fieldwork
12/13/83-02/02/84	John Lower	Costa Rica	UNA/UCR		Seismic network installation
04/01/84-01/31/85	John Lower	Costa Rica	UNA/UCR		Strong ground motion network installation
01/10/85-01/29/85	John Lower	Costa Rica	UNA/UCR		
04/22/84-04/27/84	Karen McNally	Costa Rica	UNA/UCR		Project review
08/02/84-08/14/84	Karen McNally	Costa Rica	&		Project review and budget development
12/09/84-12/12/84	Karen McNally	Costa Rica	EMBASSY		
05/15/84-05/19/84	Alejandro Nava	Costa Rica	UNA		Network operation training
08/15/83-09/20/83	Mark Reagan	Costa Rica			Thesis fieldwork
12/22/83-03/05/84	Mark Reagan	Costa Rica	UNA		Thesis fieldwork
07/18/84-07/25/84	Mark Reagan	Costa Rica	UNA		Emergency - Arenal Eruption
01/10/85-01/29/85	Mark Reagan	Costa Rica	UNA		Thesis fieldwork
12/11/83-12/18/83	Eli Silver	Costa Rica	UNA		Project coordination
01/10/85-01/29/85	Stuart Wilkinson	Costa Rica	UNA	Mark Reagan	Thesis fieldwork

APPENDIX F

TECHNICAL ANALYSIS OF VOLCÁN ARENAL

Chemical analyses have been performed on 20 samples collected from the most recent eruption of Volcan Arenal, including analysis for the following major elements: Niobium (Nb), Yttrium (Y), Strontium (Sr), and Rubidium (Rb) data on all samples, and Nickle (Ni), Chromium (Cr), Scandium (Sc), Vanadium (V), Barium (Ba), Cerium (Ce), and Neodymium (Nd) data on fourteen samples.

Three stages of chemical variation are delineated for the Arenal eruption. Stage one represents the time between the beginning of the eruption in 1968 and late 1969 when silicon dioxide (SiO_2) dropped from 56% to its lowest level at 54%. Magnesium-oxide (MgO) increased during the same period. Stage two is the time between late 1969 and 1971 when Magnesium oxide (MgO) increased while silicon dioxide remained constant. Stage three represents the rest of the eruption. During this stage SiO_2 increases while MgO remains constant.

The explanation for the above trends is that the early erupted tephra and lavas of stage one represent the differentiated, volatile-rich cap of a deep crustal magma chamber; the chemical change during stage two represents the change from the unmixed stage one lavas to mixed lavas of stage three; and the change during stage three requires open-system behavior with intrusion of new magma and crystal removal causing the change in chemistry. This model has implications for the continuing hazards potential of Volcan Arenal. It suggests that Arenal's lavas may continue to increase in silicon-dioxide with time, and as Arenal continues to erupt, it will probably become more explosive. It is unlikely though, that Arenal will approach the explosiveness it had in 1968 because recent hydrogen isotope and water content data suggest that Arenal's magmas are being effectively degassed.

APPENDIX G

VOLCAN TURRIALBA STRATIGRAPHY

The following pages describe eleven stratigraphic units which were analyzed from eight samples (A-H) taken from the summit of Volcan Turrialba. Figure 30 shows the summit geology of Volcan Turrialba and Figure 31 indicates the stratigraphy of Turrialba crater as discussed below.

UNIT 11: The oldest volcanic sequence in Turrialba crater, unit 11, includes lava flows exposed around the perimeter of the Central Crater and lava flows erupted at the south end of the Turrialba volcanic edifice. The flows at the south end of Turrialba underlie a pyroclastic flow, composed of a mixture of hot volcanic rock fragments and gasses, dated at approximately 8250 radiocarbon years before present (b.p.).

UNIT 10: On the northwest side of the Central Crater, unit 11 is overlain by a series of interbedded lava flows and near-vent pyroclastic rocks, or deposit of volcanic rock fragments. Unit 10, the oldest interbedded unit, is composed mostly of near vent pyroclastic rocks.

UNIT 9: The overlying unit, unit 9, consists of a lower section of interbedded lavas and pyroclastic rocks, and an upper section of talus deposits (a sloping mass of rocky fragments). Lavas and fragmental rocks found in the southwest side of the West Crater are similar in chemistry to rocks of unit 9 and were probably erupted during the same episode.

UNIT 8 & UNIT 7: A major erosional unconformity (of an unknown age) overlies unit 9 in the Central Crater. Lava flows of unit 8 and fragmental volcanics of unit 7 erupted next. Lake beds exposed in the southern part of the West Crater clearly predate the debris avalanche event (described below) and suggest that crater formation occurred during eruption of unit 7.

UNIT 6: One of the largest volume eruptions in the history of Volcan Turrialba followed the eruption of unit 7. It produced a series of lava flows, unit 6, that covered the entire 180° northeast sector of Volcan

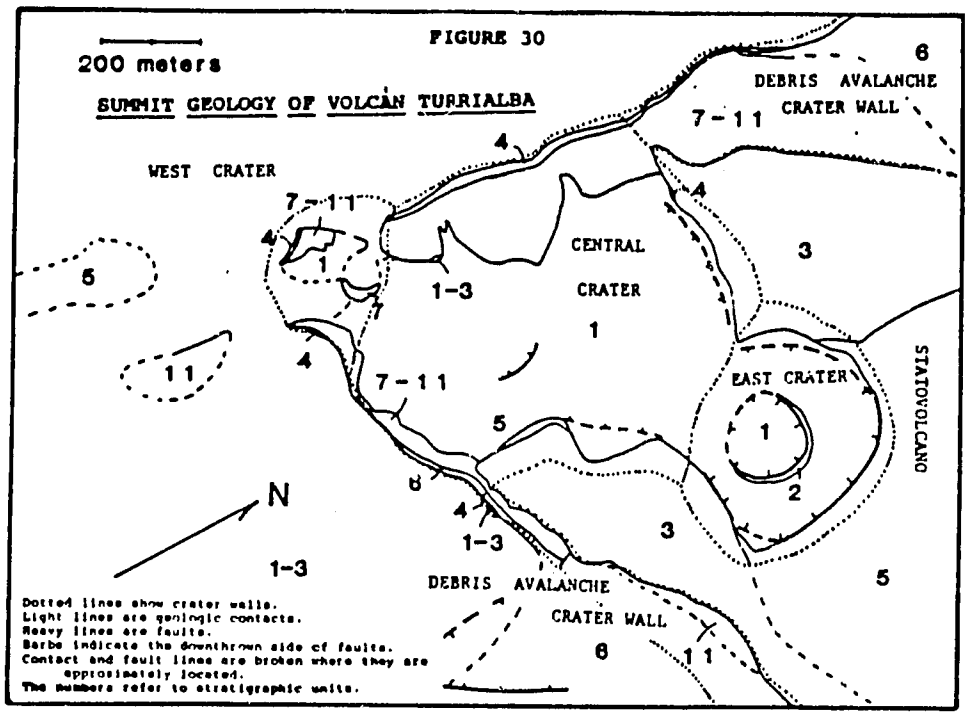


FIGURE 30
200 meters
SUMMIT GEOLOGY OF VOLCÁN TURRIALBA
WEST CRATER
CENTRAL CRATER
EAST CRATER
DEBRIS AVALANCHE
CRATER WALL
STRATOVOLCANO
N
Dotted lines show crater walls.
Light lines are geologic contacts.
Heavy lines are faults.
Barbs indicate the downthrown side of faults.
Contact and fault lines are broken where they are approximately located.
The numbers refer to stratigraphic units.

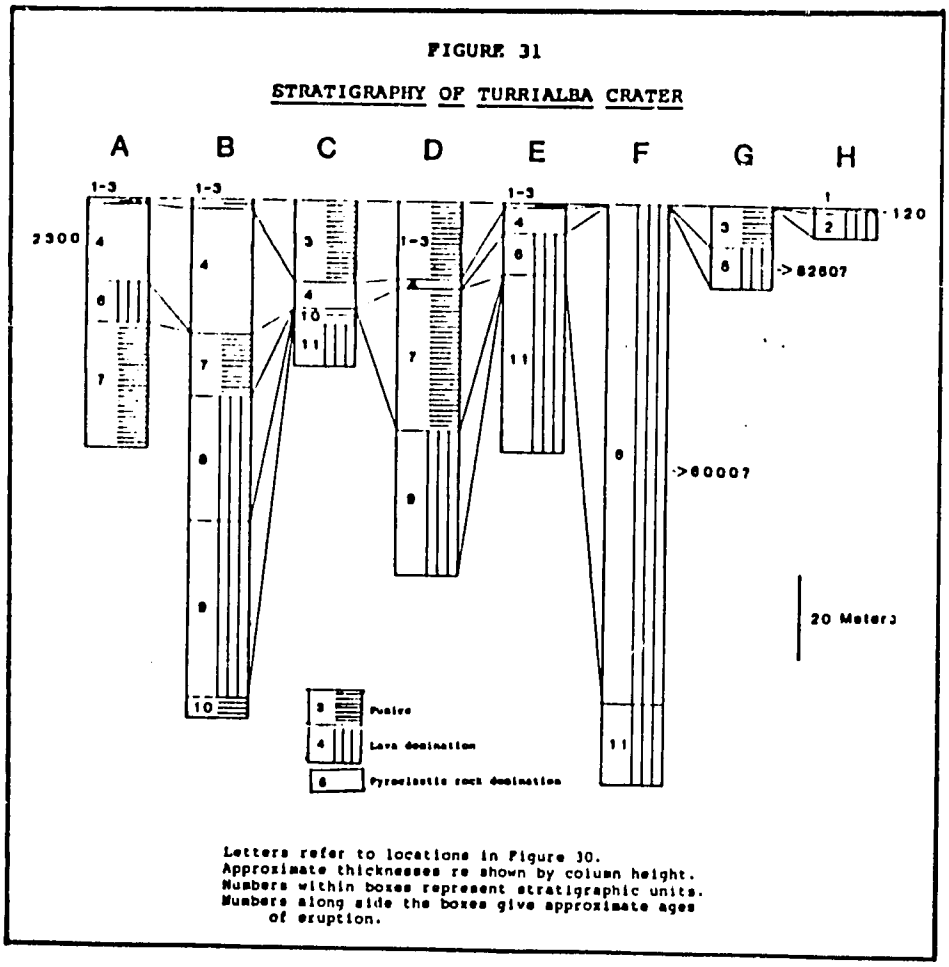


FIGURE 31
STRATIGRAPHY OF TURRIALBA CRATER
A
B
C
D
E
F
G
H
2300
120
>82607
>60007
20 Meters
Pumice
Lava domination
Pyroclastic rock domination
Letters refer to locations in Figure 30.
Approximate thicknesses re shown by column height.
Numbers within boxes represent stratigraphic units.
Numbers along side the boxes give approximate ages of eruption.

Turrialba. Over 100m of these flows are exposed on the southern wall of the debris avalanche crater and over 140m are exposed on the northwest wall. Recent thorium (Th) and radium (Ra) isotope work suggest that unit 6 is greater than 6000 years old. (This date should be used with caution until further isotopic analyses of Turrialba rocks have been done.) All of the deposits discussed so far are andesites and dacites, with silicon dioxide (SiO2) contents ranging from 54.5% to 64.1%.

EVENT: Following a period of quiescence and erosion, a major debris avalanche took away most of the northeast side of Volcan Turrialba. Approximately 1-2 km^3 of the volcano broke away from the volcano and flowed approximately ten kilometers to the northeast during this event.

UNIT 5: Unit 5 comprises lavas of the stratovolcano and a thick dacite flow from the Central Crater. SiO2 contents of these volcanics range from 54.9% to 63.4%, which suggests that more than one eruption may have been involved in their production. One of these eruptions may be represented by a greater than 8250 radiocarbon dated lava flow that lies in Turrialba's southern flank.

A symmetrical stratovolcano built up in the north side of the debris avalanche crater following eruption of the pumice. Lavas from the stratovolcano have flowed up to 10-12 km to the north and northeast of Turrialba.

UNIT 4: Coarse pumice (SiO_2 = 58% - 59%) of unit 4 erupted after the stratovolcano and was deposited over most of western Costa Rica. The pumice is up to 40 meters thick on the rim of Turrialba Crater and 1.3 meters thick 2.5 kilometers from the summit. Two radiocarbon dates constrain the timing of this eruption to around 2300 years b.p. (A 2590 year date was obtained from charcoal in a soil horizon underlying the pumice, and a log composed of peat from within the pumice deposit gave a date of 2330 years b.p.)

UNIT 3: Near-vent pyroclastic deposits of unit 3 form a mantle around the stratovolcano and compose part of the deposits located on the debris avalanche crater rim. The minerology and chemical variations within unit 3 appear to reflect the mixing of low and high silicon dioxide magmas.

UNIT 2: An enigmatic lava flow located in the walls of a small collapse crater within the East Crater (unit 2) appears to have erupted next. It is enigmatic because it has a chemical composition similar to that in

earlier units, but is only overlain by unit 1. The eruption of unit 3 was accompanied by caldera formation in the stratovolcano and was followed by formation of a lava lake in the resulting small caldera (unit 2).

UNIT 1: The youngest unit, unit 1, erupted in 1863-1865. Remains of the eruption are found throughout the summit area and are composed exclusively of basalt with a SiO_2 content between 51.5% and 53%.

Another small caldera formed within the previous caldera during the 1863-5 eruption. This eruption was also accompanied by crater formation in the central vent area and by phreatic explosions in the West Crater. These relationships suggest a complicated plumbing system for the Turrialba magma system, because different types of activity occurred simultaneously in the three summit craters during recent eruptions.

APPENDIX H

EARTHQUAKE INTENSITY MAPS

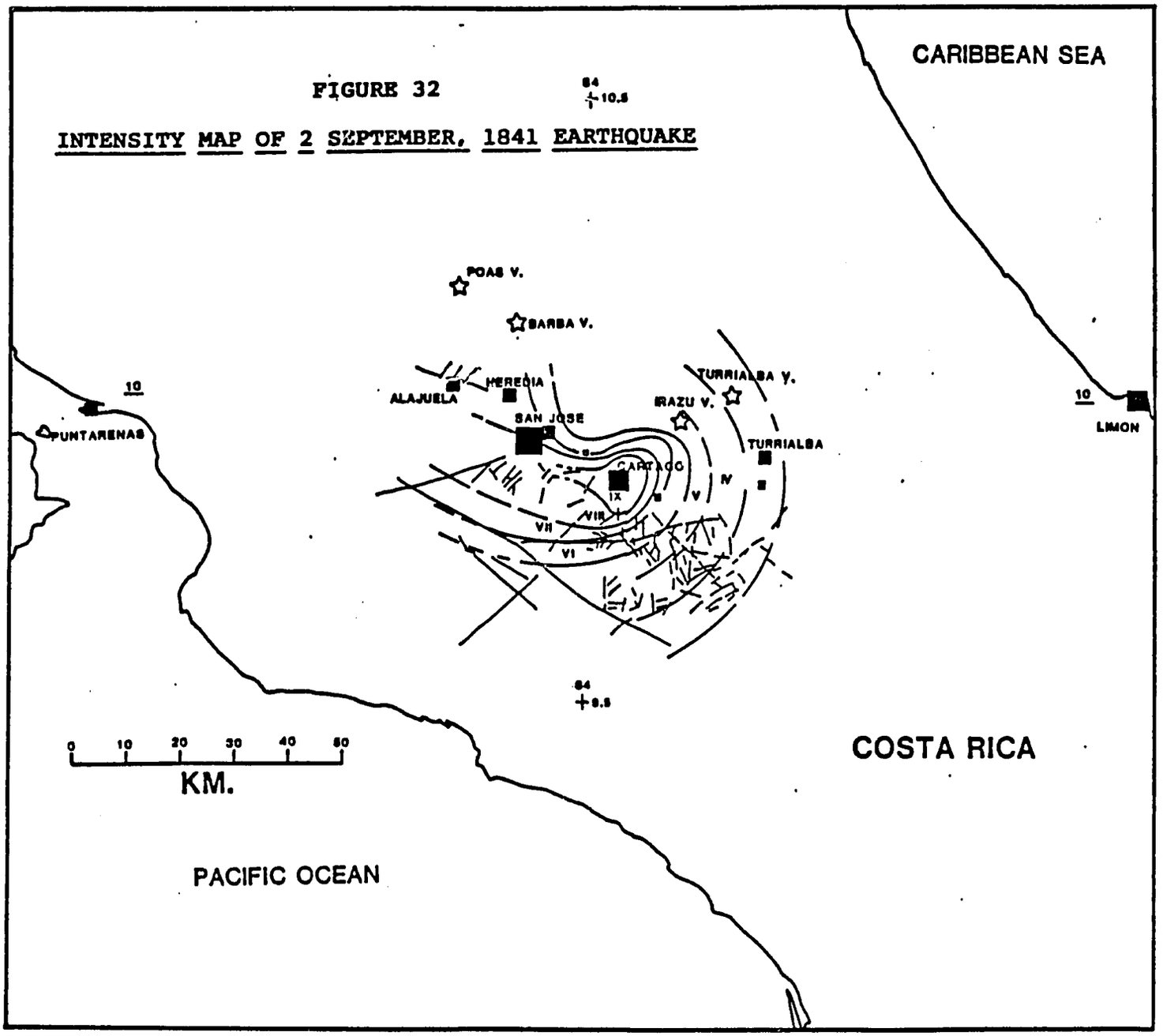
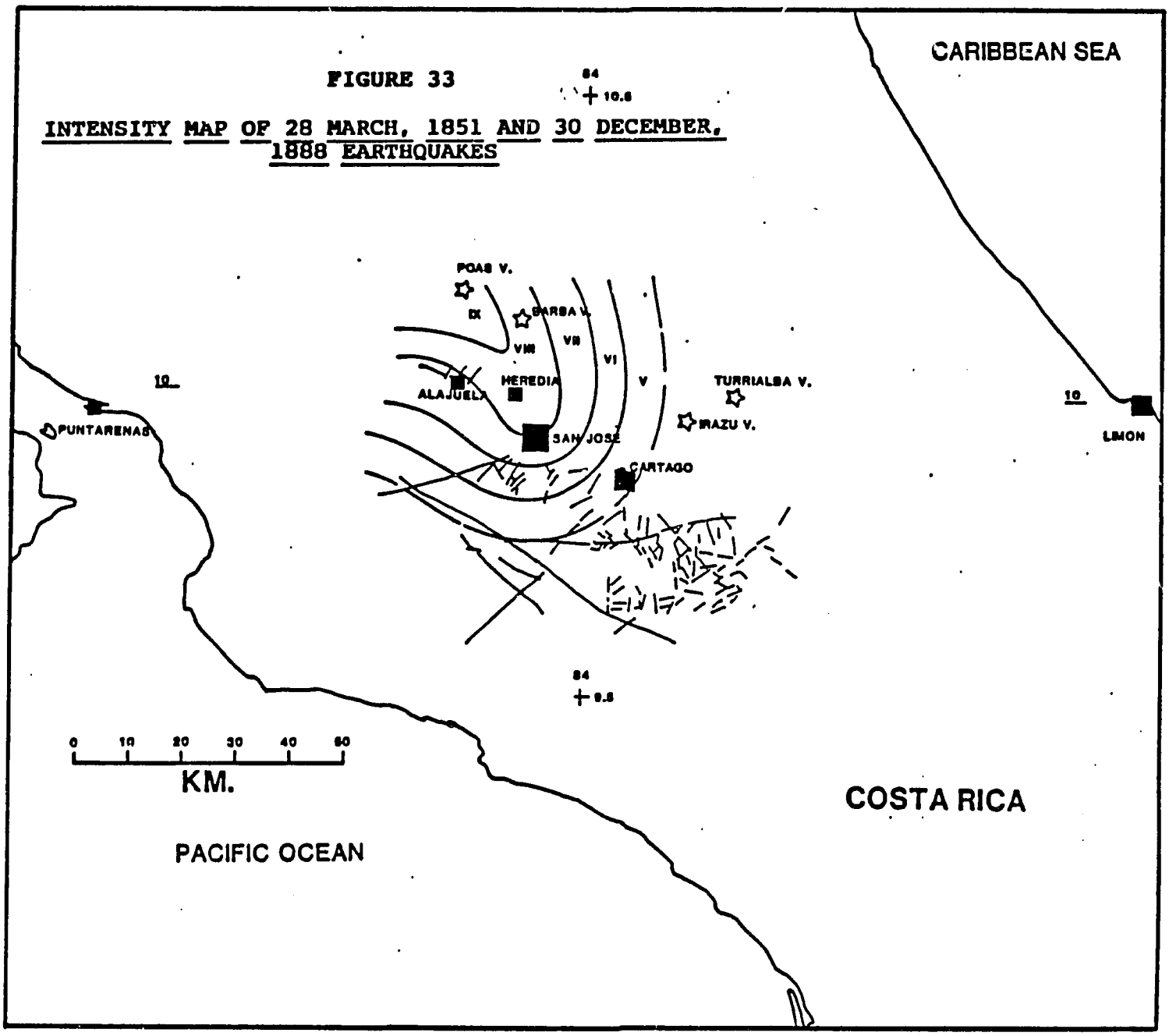


FIGURE 32

INTENSITY MAP OF 2 SEPTEMBER, 1841 EARTHQUAKE

FIGURE 33

INTENSITY MAP OF 28 MARCH, 1851 AND 30 DECEMBER, 1888 EARTHQUAKES



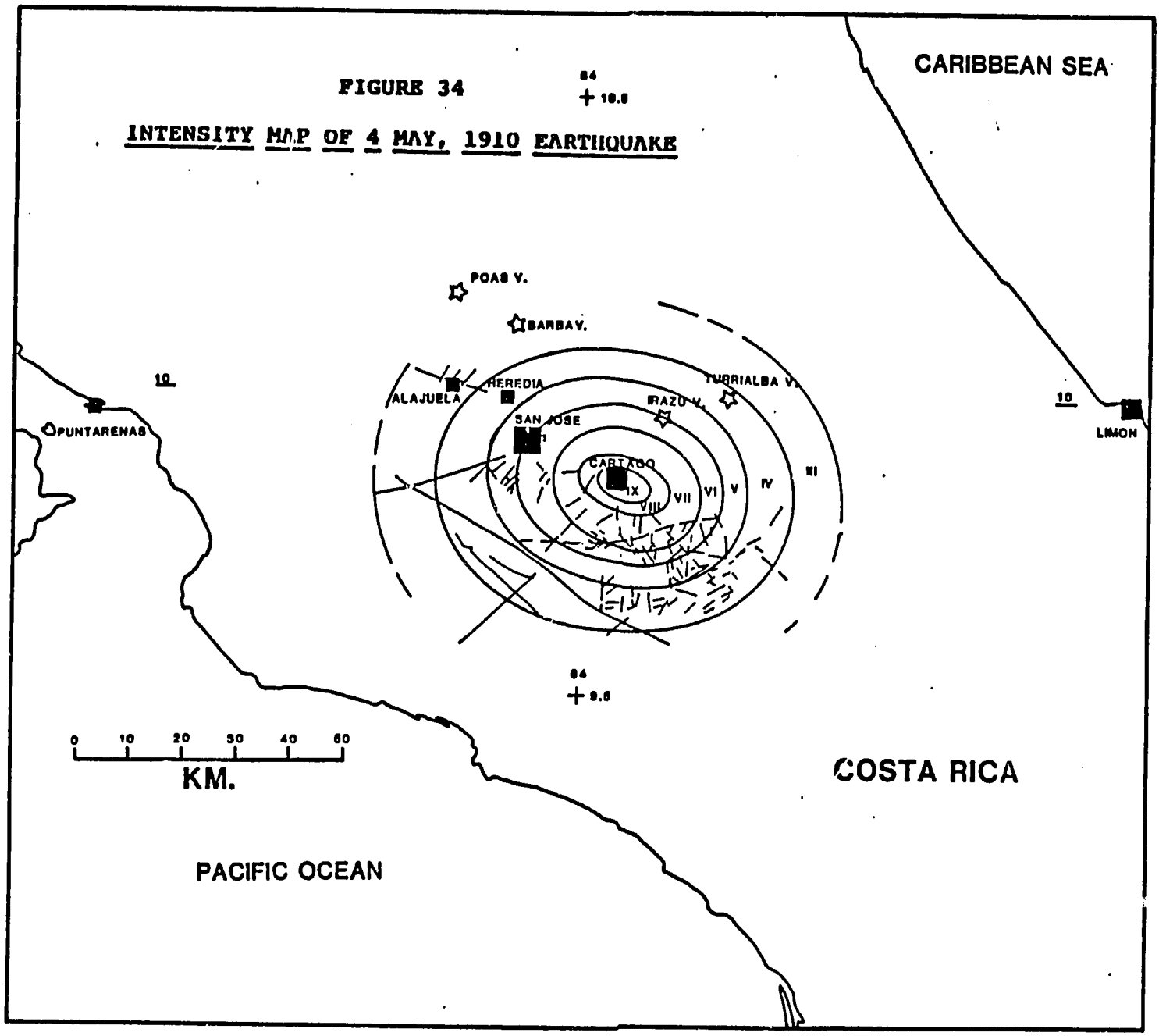


FIGURE 34

INTENSITY MAP OF 4 MAY, 1910 EARTHQUAKE

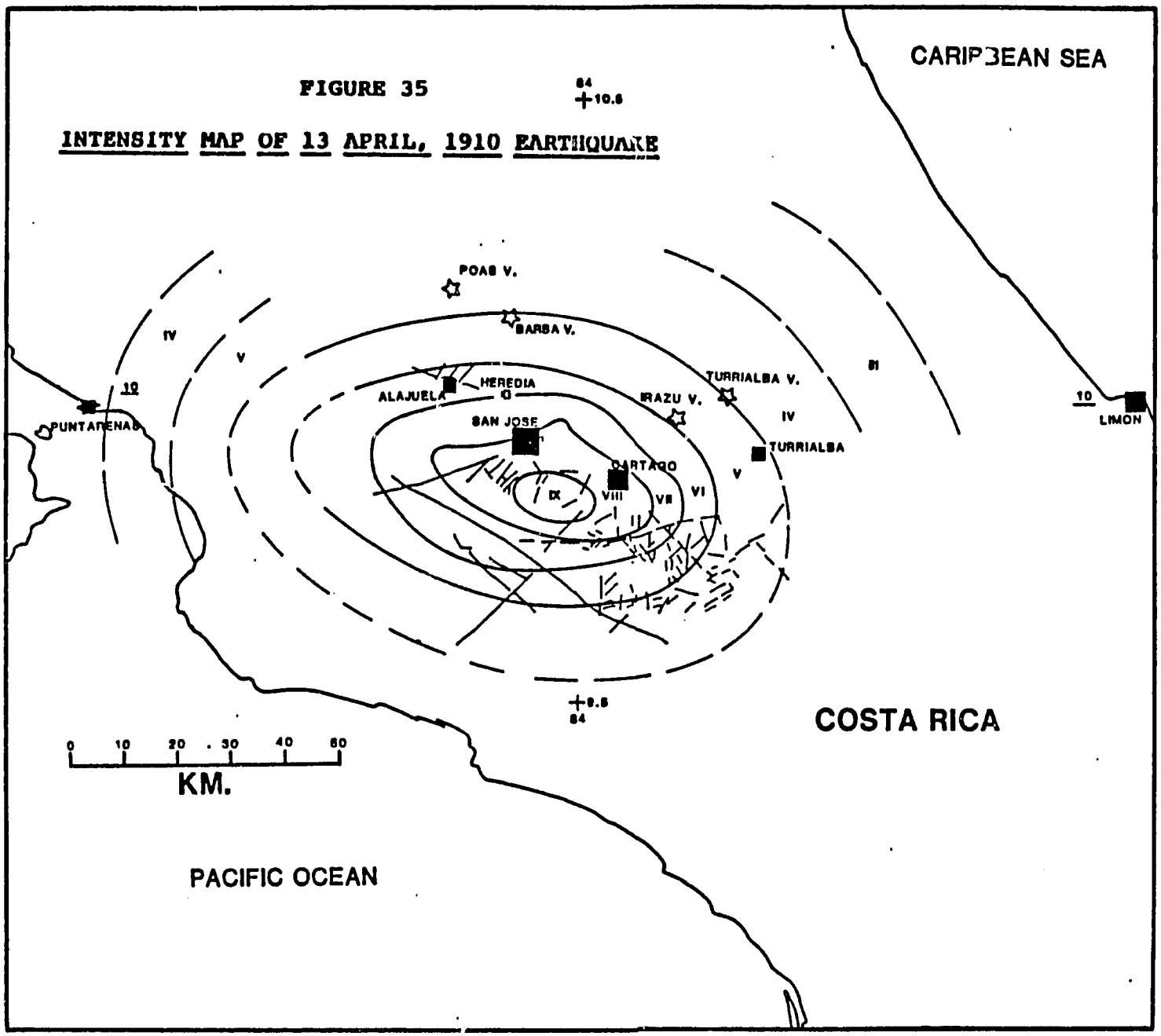


FIGURE 35

INTENSITY MAP OF 13 APRIL, 1910 EARTHQUAKE

APPENDIX I

MODIFIED MERCALLI SCALE

Intensities and Isoseismals

INTENSITY SCALES

In Mallet's day it was becoming generally known that the distribution of the macroseismic effects of earthquakes could be represented by the drawing of isoseismals, or lines of equal apparent intensity of shaking.

Special Scales

At first each earthquake was quite properly investigated independently; even at the present time this is considered good practice. Especially when a large earthquake is being investigated and many observations are being correlated, it is scientifically preferable to begin by setting up isoseismals with reference to local conditions of terrain and construction. After this is done, the isoseismals may be correlated with those of some more generally applicable scale.

Local conditions sometimes almost force a special scale on the investigator. Thus, workers who took the field after the Turkish earthquake of 1939 found that conventional intensity scales failed to describe the damage to the tamped-earth construction common in that region, and they fell back on estimates of the percentage of damage in the various localities.

The Rossi-Forel Scale

Intensity scales intended for general application developed gradually, as the comparison of individual investigations led toward a common pattern. De Rossi in Italy and Forel in Switzerland, who had been working in this direction more or less independently, joined forces in 1883 to set up the Rossi-Forel scale. It was widely adopted. In seismological and engineering literature, when no particular scale is specified, earthquake intensity is usually expressed in terms of this scale; it is commonly indicated by the abbreviation R.F. followed by the Roman numeral of the scale degree. The scale is reproduced in Appendix III.

With the general advance of technology the R.F. scale grew progressively

more out of date. An enormous range of intensity was lumped together at its highest level, X. Moreover, the descriptions of effects both on construction and on natural objects proved to be too specifically European.

The Mercalli Scale

These defects were largely removed in an improved scale put forward by Mercalli in 1902 at first with ten grades of intensity, later with twelve following a suggestion by Cancani who attempted to express these grades in terms of acceleration. An elaboration of the Mercalli scale, including earthquake effects of many kinds and ostensibly correlated with Cancani's scheme, was published by Sieberg in 1923. This form was in turn used as the basis for the Modified Mercalli Scale of 1931 (commonly abbreviated M.M.) by H. O. Wood and Frank Neumann.†

Modified Mercalli Scale Restated

The original publication gives the M.M. scale in two forms: one a lengthy statement modeled on that of Sieberg, with additions and modifications suggested by later experience; the other an abridgment meant for rough-and-ready use. The abridged form was prepared chiefly by one author, and at a few points is in conflict with the main scale. At the risk of putting a third version into circulation, this chapter presents an expansion of the shorter form, including most of the items in the complete form. Some items are omitted for definite reason, and a few additional notes are included, with initials (CFR) to separate them from the scale proper. Additional whys and wherefores of a technical nature will be found in Appendix III.

To eliminate many verbal repetitions in the original scale, the following convention has been adopted. Each effect is named at that level of intensity at which it first appears frequently and characteristically. Each effect may be found less strongly, or in fewer instances, at the next lower grade of intensity; more strongly or more often at the next higher grade. A few effects are named at two successive levels to indicate a more gradual increase.

Masonry A, B, C, D. To avoid ambiguity of language, the quality of masonry, brick or otherwise, is specified by the following lettering (which has no connection with the conventional Class A, B, C construction).

Masonry A. Good workmanship, mortar, and design; reinforced, especially laterally, and bound together by using steel, concrete, etc.; designed to resist lateral forces.

Masonry B. Good workmanship and mortar; reinforced, but not designed in detail to resist lateral forces.

† A modification suited to conditions in the USSR has been worked out by Medvedev.

Masonry C. Ordinary workmanship and mortar; no extreme weaknesses like failing to tie in at corners, but neither reinforced nor designed against horizontal forces.

Masonry D. Weak materials, such as adobe; poor mortar; low standards of workmanship; weak horizontally.

Modified Mercalli Intensity Scale of 1931 (Abridged and rewritten†)

I. Not felt. Marginal and long-period effects of large earthquakes (for details see text).

II. Felt by persons at rest, on upper floors, or favorably placed.

III. Felt indoors. Hanging objects swing. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake.

IV. Hanging objects swing. Vibration like passing of heavy trucks; or sensation of a jolt like a heavy ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. In the upper range of IV wooden walls and frame creak.

V. Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move. Pendulum clocks stop, start, change rate.

VI. Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Knickknacks, books, etc., off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster and masonry D cracked. Small bells ring (church, school). Trees, bushes shaken (visibly, or heard to rustle—CFR).

VII. Difficult to stand. Noticed by drivers of motor cars. Hanging objects quiver. Furniture broken. Damage to masonry D, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices (also unbraced parapets and architectural ornaments—CFR). Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slides and caving in along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged.

VIII. Steering of motor cars affected. Damage to masonry C; partial collapse. Some damage to masonry B; none to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.

IX. General panic. Masonry D destroyed; masonry C heavily damaged, sometimes with complete collapse; masonry B seriously damaged. (General damage to foundations—CFR.) Frame structures, if not bolted, shifted off

† The author takes full responsibility for this version, which, he believes, conforms closely to the original intention. He requests that, should it be necessary to specify it explicitly, the reference be "Modified Mercalli Scale, 1956 version," without attaching his name. The expression "Richter scale" is popularly attached to the magnitude scale; it is desirable to forestall confusion between magnitude and intensity.

foundations. Frames racked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluviated areas sand and mud ejected, earthquake fountains, sand craters.

X. Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.

XI. Rails bent greatly. Underground pipelines completely out of service.

XII. Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air.

Long-Period Effects. The most important general consideration in applying such a scale is that it brings together long-period and short-period effects. The latter are in the majority and may be roughly correlated with acceleration. The long-period effects represent large displacement, which often goes with comparatively moderate acceleration. With increasing magnitude the proportion of long-period to short-period phenomena tends to increase at all distances from the epicenter. Since the scale in general places the long-period effects where they appear during earthquakes of moderate magnitude, serious confusion has sometimes arisen in dealing with large shocks.

Large landslides, particularly those of the earth-slump type, are typical long-period effects; they are triggered more readily by large slow motion than by rapid shaking. This is the effect referred to in assigning large slides to X. Smaller slides, many of them of the earth-avalanche type, are common, as indicated, at intensity VII. However, great earthquakes sometimes precipitate large slumps in distant areas where the intensity is otherwise indicated as low as VI. Cracks and fissures, especially those due to earth lurches, behave similarly, so that intensity from such evidence has to be assigned with some reference to magnitude. The same applies to effects on works of construction where a long-period resonance is involved, as in the swaying and distortion of tall buildings or towers and in the overturning of elevated tanks.

A special group of long-period effects is that referred to under I. The complete scale lists them as: dizziness or nausea; birds or animals uneasy or disturbed; swaying of trees, structures, liquids, bodies of water; doors swing slowly. The swinging of chandeliers may be added. All these may be observed when no actual shaking is perceptible. Many of them are pendulum effects; chandeliers and large branches of trees may act as long-period seismoscopes. The oscillation of bodies of water is analogous; these effects are seiches (Chapter 9). The increased number of such observations with higher magnitude depends in part on the greater proportion of long-period motion. There is another factor of importance: intensity measured by any

reasonable criterion falls off with increasing distance at first rapidly and then more and more slowly. For relatively small magnitude, the limiting distance for perceptibility is short, and the range of distance over which intensity is close to the limiting level is narrow. For large magnitude, intensity decreases gradually near the limiting distance, and the critical zone of marginal effects expands into a broad band surrounding the area of intensity II.

Other Notes on the M.M. Scale. Intensity II is often characterized as "felt by few," since usually a small proportion of a large group will notice shaking at this level. The increased perceptibility on upper floors, some years ago still regarded with doubt, has been put beyond question by recordings from strong-motion instruments operated by the U. S. Coast and Geodetic Survey simultaneously in the basements and on the upper floors of tall buildings in California. In practically every instance the instrument on the upper floor shows notably larger recorded motion.

Intensity III is an "in-between" intensity with no characteristic effect of its own; observations which seem too much for II and too little for IV are assigned to it. Intensity IV, on the other hand, is marked by a number of characteristic effects; in a well-investigated earthquake it can usually be separated into an upper and a lower level.

Intensity IX is another "in-between" level. General damage to ordinary foundations, however, is characteristic and has been added here. Ejection of sand and water, particularly in the form of earthquake fountains (Chapter 9), beginning on a small scale at VIII, becomes notable at this level provided that the necessary subsurface conditions exist; large and spectacular phenomena of this sort belong to X.

At intensities X, XI, and XII the 1931 M.M. scale describes some effects which are primary rather than secondary and hence are doubtful indicators of the degree of shaking. Disturbance in the immediate vicinity of a moving fault appears to depend largely on the nature of the ground. Ordinary structures located close to the fault trace in 1906 were not shaken with extreme violence. One barn was actually dragged off its foundations and shifted 15 feet by the faulting without being destroyed, and at the same place a brick chimney remained standing. On the other hand, great damage was done to redwood trees close to the fault trace, indicating large amplitudes in the long-period motion which snapped off their branches. In Imperial Valley in 1940 weak adobe structures close to the fault trace were injured no more than those several miles distant. A different description applies to Oldham's observations in 1897, where the fault traces broke through sound igneous rock, and there was every evidence of extreme violence in the immediate vicinity. For this reason the M.M. scale under XII specifies "Fault slips in firm rock."

FIGURE 36

SYNTHETIC WAVEFORM MODEL

FEBRUARY 28, 1974
Ms: 6.2
STRIKE: 296
DIP: 20
RAKE: 90

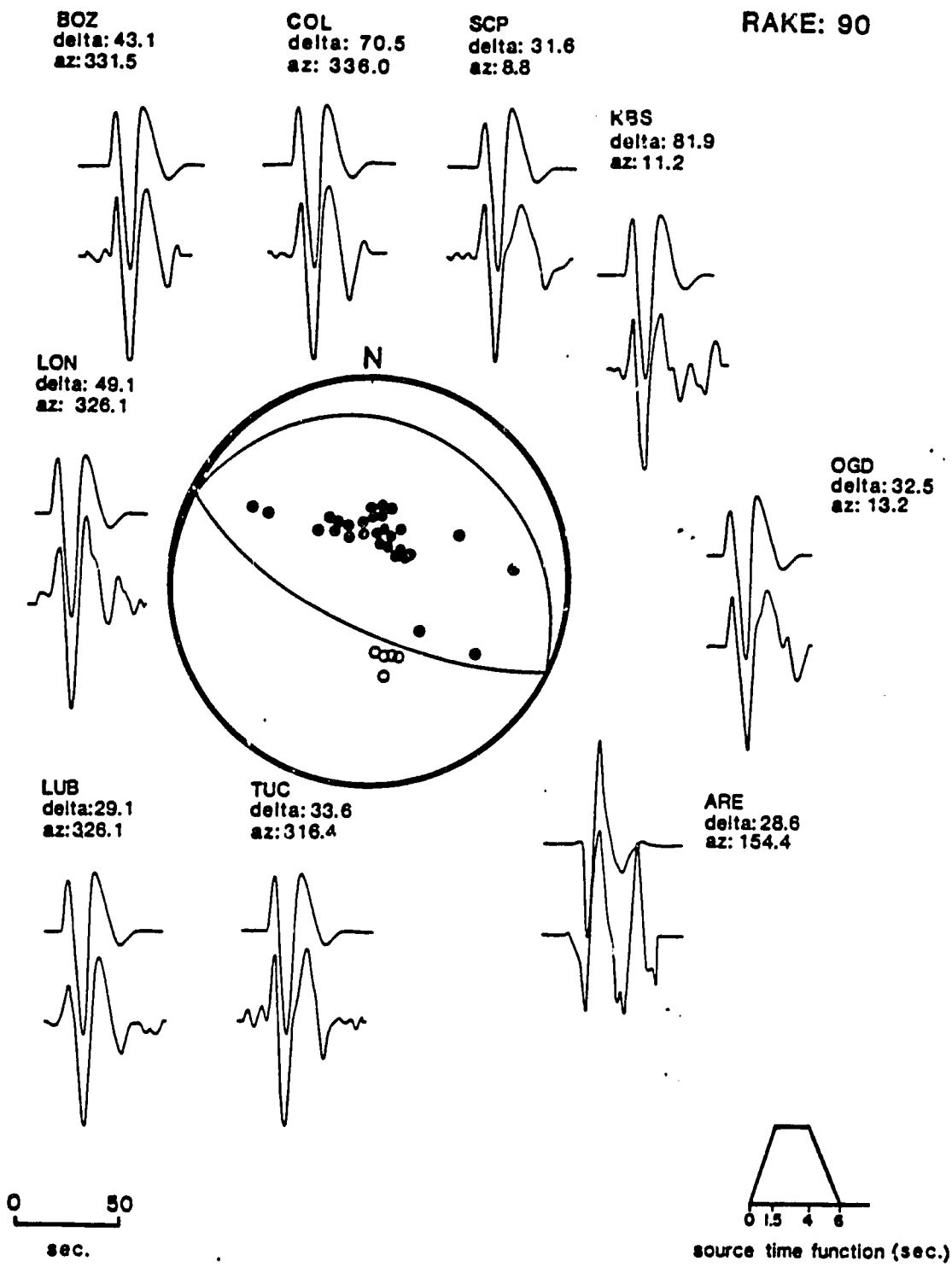


FIGURE 37

SYNTHETIC WAVEFORM MODEL

AUGUST 23, 1978
Ms:7.0
STRIKE: 298
DIP: 22
RAKE: 100

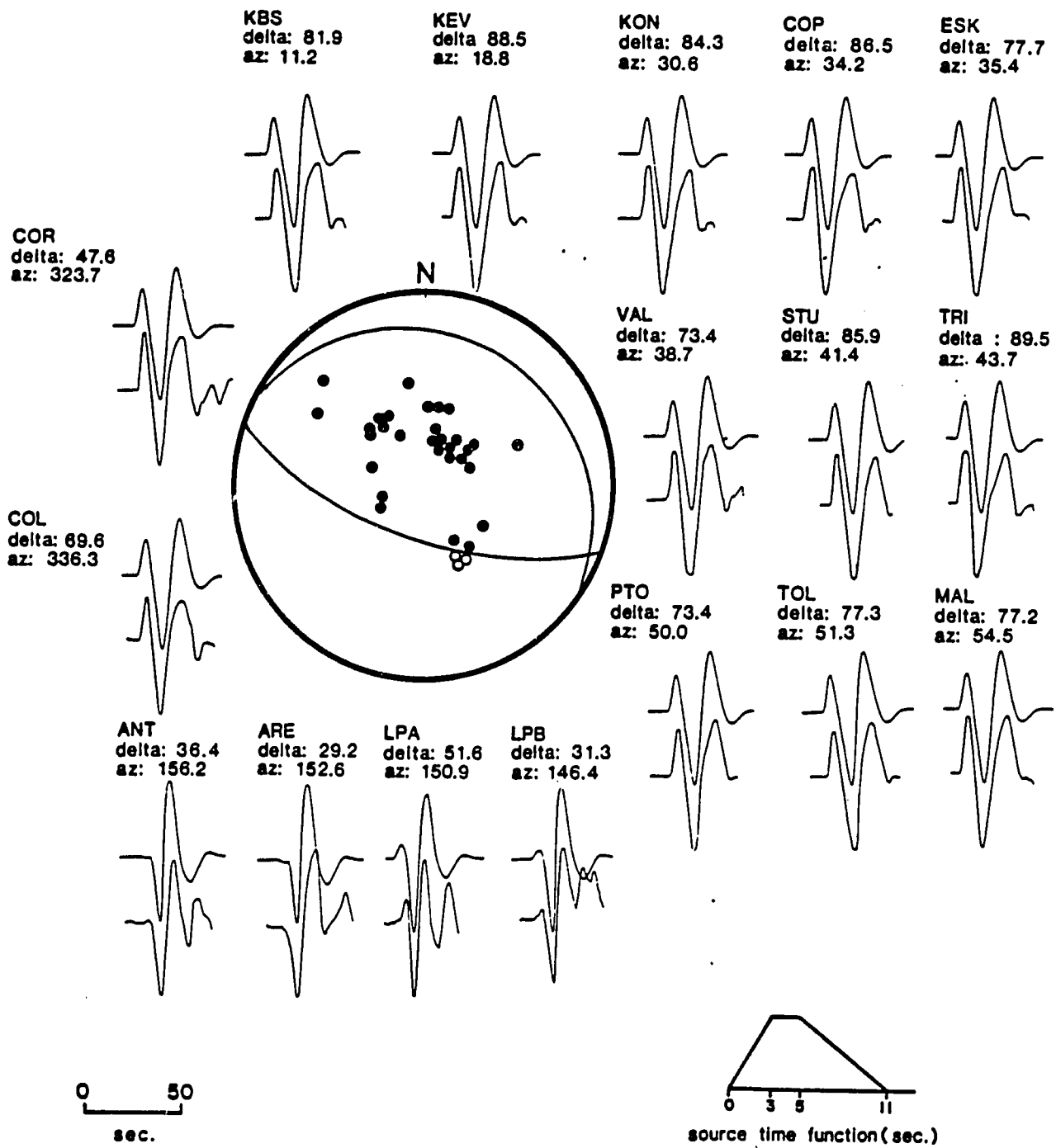


FIGURE 38

SYNTHETIC WAVEFORM MODEL

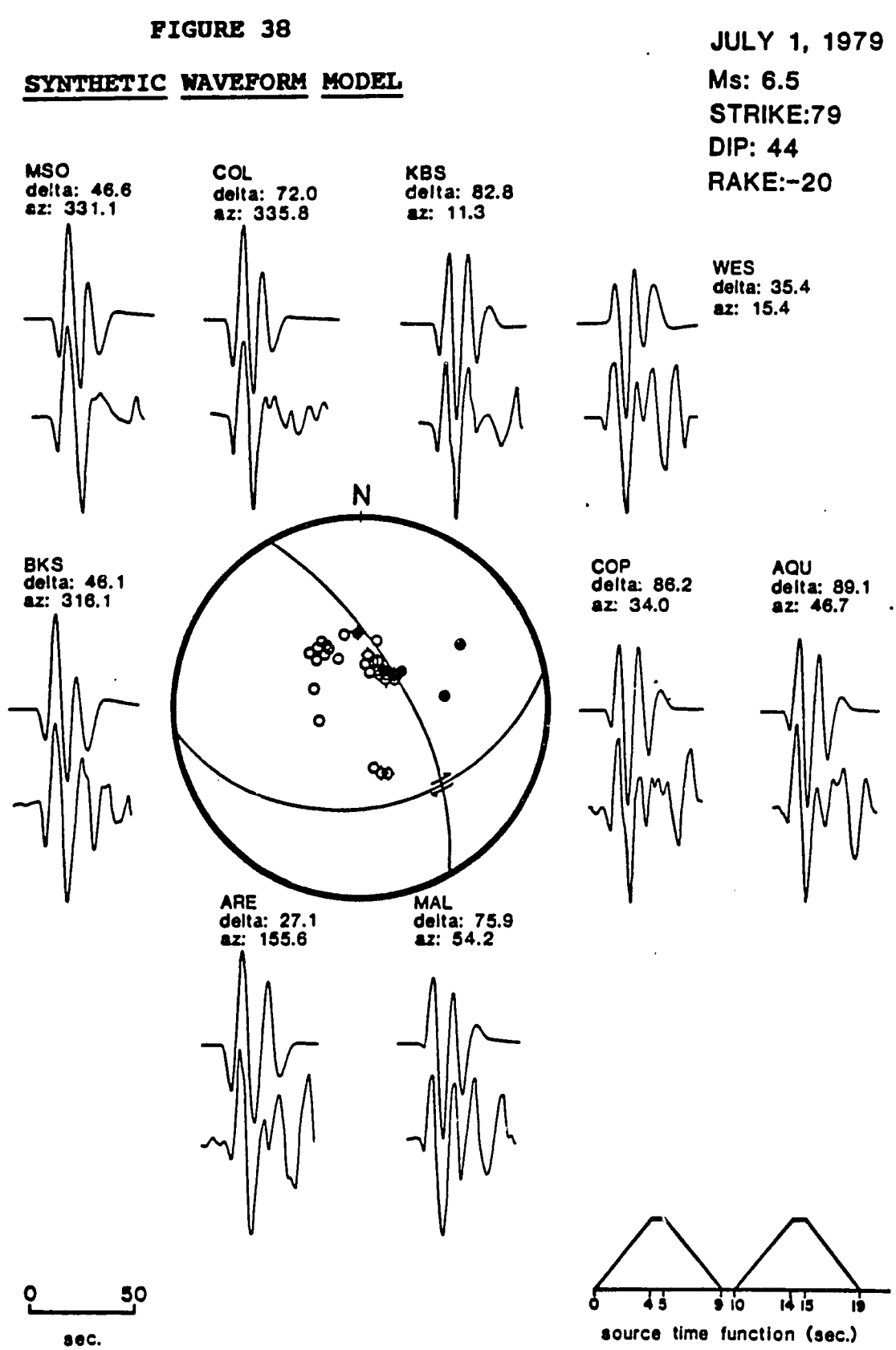


FIGURE 39

SYNTHETIC WAVEFORM MODEL

AUGUST 24, 1979
Ms: 6.4
STRIKE: 239
DIP: 44
RAKE: 28

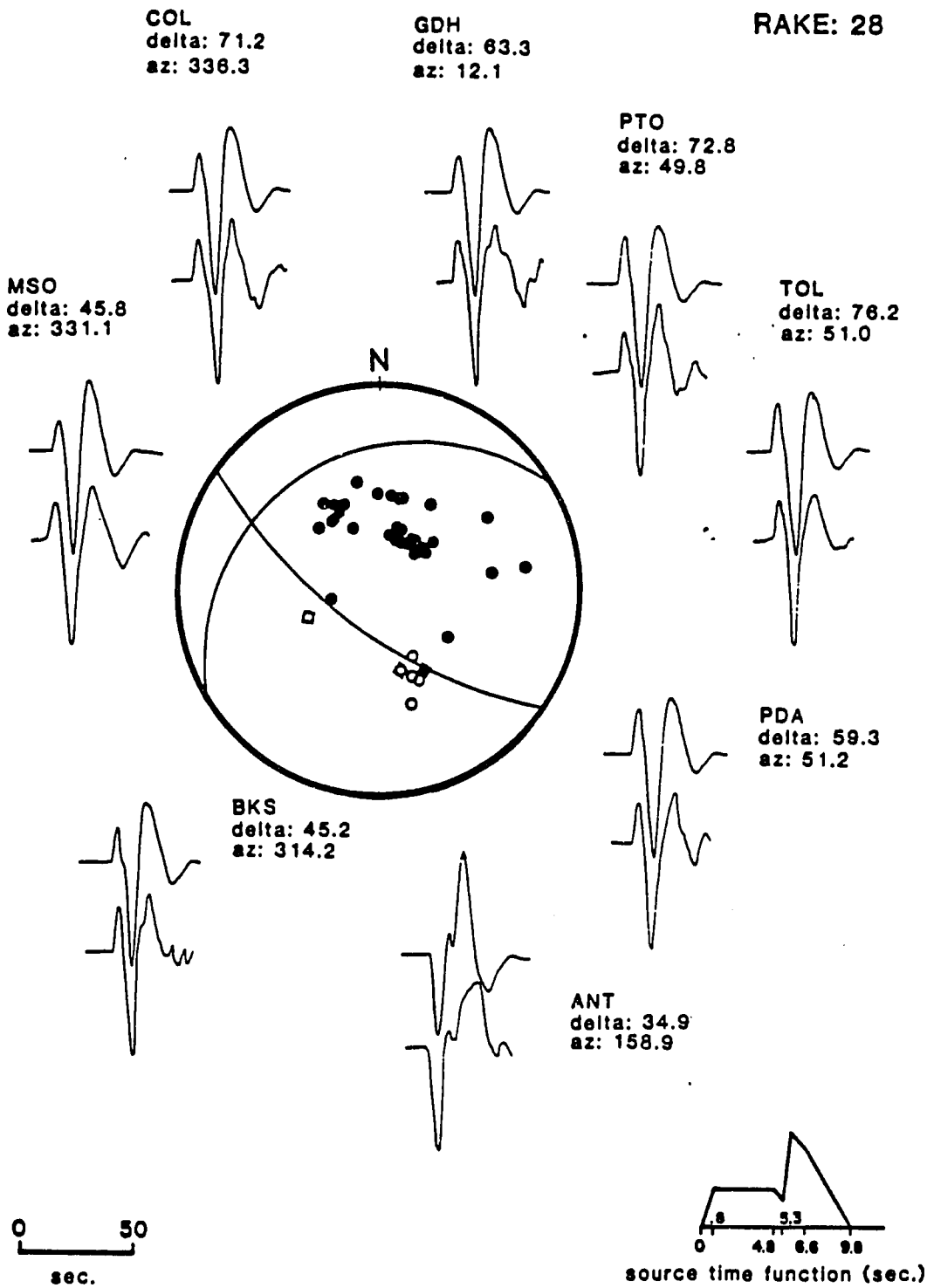
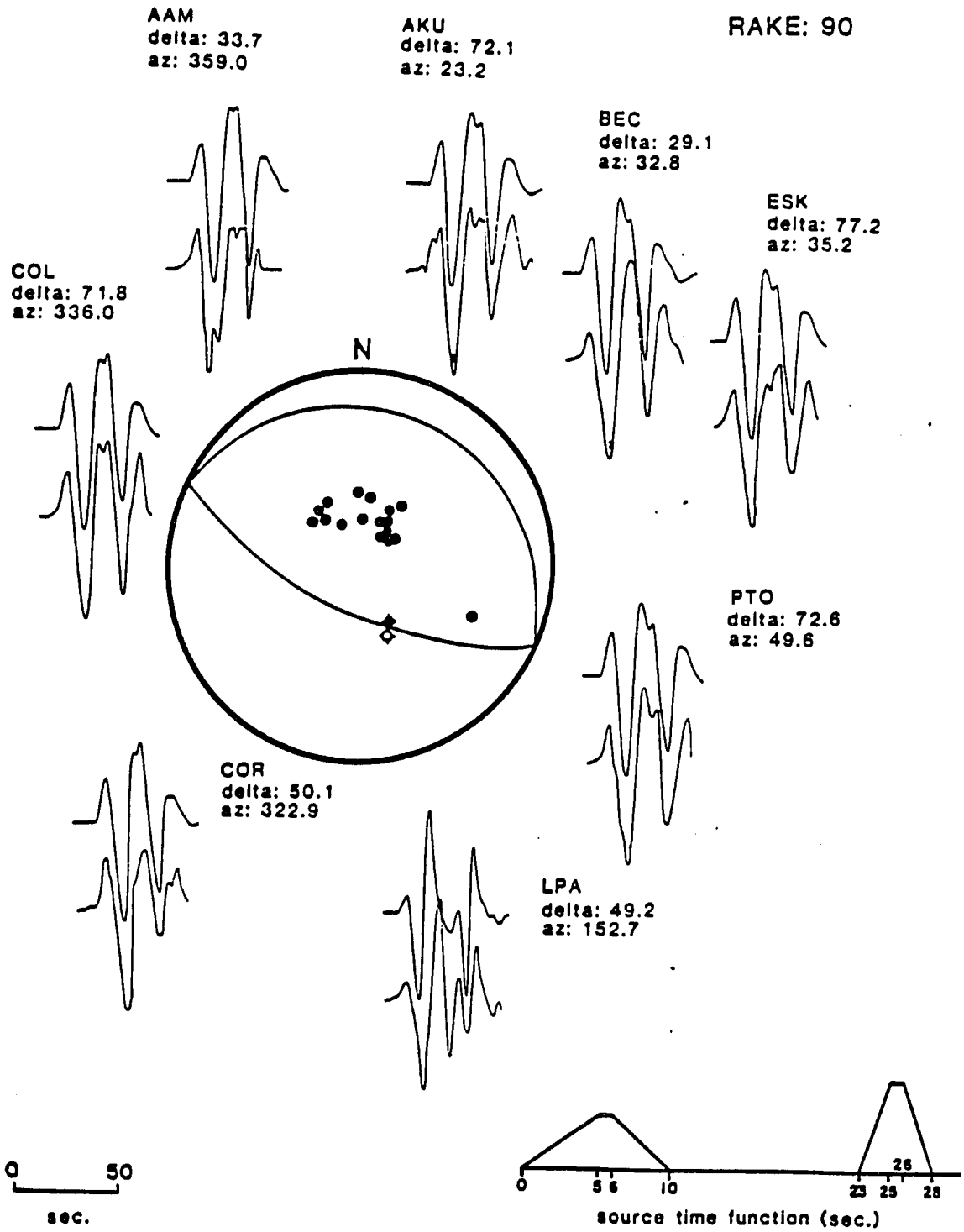


FIGURE 40

SYNTHETIC WAVEFORM MODEL

APRIL 3, 1983
Ms: 7.3
STRIKE: 295
DIP: 20
RAKE: 90