EARTHQUAKE INSTRUMENTATION FOR UTAH
Report and Recommendations of the Utah Policy Panel on Earthquake Instrumentation

edited by
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Earthquake Instrumentation for Utah

Report and Recommendations of the Utah Policy Panel on Earthquake Instrumentation

August 25, 1989

(Revised October 17, 1989)

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Co-Chairmen

Senator Craig A. Peterson (Republican), a practicing engineer, has served in the Utah State Senate since 1988 and earlier served in the State House of Representatives from 1986 to 1988. Senator Peterson has a B.S. degree in manufacturing engineering technology from Weber State College and completed graduate studies in business administration at Texas State University, Corpus Christi.

(Former) Representative John P. "Jack" Redd (Republican), a consulting engineer, served in the Utah State House of Representatives from 1967 to 1975 and again from 1986 to 1988. He has a B.S. degree in chemical engineering from the University of Utah and was named Utah Engineer of the Year in 1968.

Members

Ed. Note: The following profiles for the respective panel members emphasize aspects of their expertise and experience relevant to this policy panel. More complete curricula vitae for the panel members are on file with the panel co-chairmen. —WJA

Clarence R. Allen (Ph.D., Structural Geology and Geophysics, California Institute of Technology, 1954) is Professor of Geology and Geophysics at the California Institute of Technology. Professor Allen is a member of the National Academy of Sciences, the National Academy of Engineering, and the American Academy of Arts and Sciences. He is also a past president of the Seismological Society of America and the Geological Society of America. An internationally-renowned expert in seismic geology, he jointly directs operations of a 250-station regional seismic network in southern California operated by Caltech and the U.S. Geological Survey.

Richard Andrews (Ph.D., Northwestern University) is Deputy Director of the Governor's Office of Emergency Services, State of California. Dr. Andrews is responsible for emergency preparedness and response activities in an eleven-county area in southern California and is manager of all earthquake programs for California's Office of Emergency Services. He has served as Executive Director of the California Seismic Safety Commission, as Director of the Southern California Earthquake Preparedness Project, and as Chairman of the Western States Seismic Policy Council. He currently is a member of the National Research Council's Panel on Real-Time Earthquake Warning Systems.

Robert M. Hamilton (Ph.D., Geophysics, University of California, Berkeley, 1965) is a prominent geophysicist of the U.S. Geological Survey, of which he has been the Chief Geologist (1982-87) [directing a $200 million research program] and Chief of the Office of Earthquake Studies (1973-78) [directing 400 people and a $32 million budget]. He has served as President of the Seismological Society of America and as President of the Seismology Section of the American Geophysical Union. Dr. Hamilton has extensive experience in earthquake seismology, including research and organizational work in 11 foreign countries.

Christopher Rojahn (M.S., Civil Engineering, and Engineer, Stanford University, 1967 and 1968, respectively) is Executive Director of the Applied Technology Council (associated with the Structural Engineers Association of California). Mr. Rojahn is expert in the fields of earthquake engineering and structural engineering and has conducted extensive research on the earthquake response of buildings, bridges, and other structures. He has participated in post-earthquake investigations in California, Hawaii, Argentina, Nicaragua, Romania, and the Soviet Union. Currently, he is a member of the Scientific Advisory Council for the National Center for Earthquake Engineering Research.

Anthony F. Shakal (Ph.D., Geophysics, Massachusetts Institute of Technology, 1979; M.S., Engineering Mechanics, University of Wisconsin, 1972) is Program Manager of the California Strong Motion Instrumentation Program—a multi-million-dollar statewide program established in California in the early 1970's "to obtain vital earthquake data for the engineering-scientific community." Dr. Shakal is both a seismologist and an engineer and has extensive research experience in engineering seismology and observational seismology.

David W. Simpson (Ph. D., Geophysics, Australian National University, Canberra, 1973) is a Senior Research Scientist and Associate Director for Seismology, Geology, and Tectonophysics, Lamont-Doherty Geological Observatory of Columbia University. Dr. Simpson is an international expert in reservoir-induced seismicity and has extensive experience with network seismology using both fixed and portable seismographic arrays. He was the Project Leader for Field Investigations of the U.S.-U.S.S.R. Working Group on Earthquake Prediction (1977-1986) and has served on numerous national-level scientific boards and committees.

James H. Whitcomb (Ph.D., Geophysics, California Institute of Technology, 1973) is Program Director for Seismology at the National Science Foundation. Dr. Whitcomb is an expert in both earthquake seismology (including earthquake-prediction research and seismic-network operations) and geodesy. During the last decade his research and work has focused on the use of extraterrestrial geodetic methods for making measurements of crustal strain—with emphasis on Global Positioning System (GPS) satellite-based technology. Prior to recently joining the National Science Foundation, he spent four years in private industry developing GPS instrumentation.

John H. Wiggins (Ph.D., Civil Engineering, University of Illinois, 1961; M.S., Geophysics, St. Louis University, 1955)—civil engineer, safety engineer, and geophysicist—is the founder and President of Crisis Management Corporation, a management consulting firm. Dr. Wiggins is an internationally prominent engineering analyst of natural and technologic hazards. He has served as chairman or member of numerous national policy-making committees under the auspices of the National Academy of Sciences, the Federal Emergency Management Agency, the National Science Foundation, the President's Office of Science and Technology Policy, the American Society of Civil Engineers, and others. His special interests lie in the area of structuring public and corporate policy using Risk Analysis and Decision Theory to mitigate, eliminate, or avoid natural, man-made, and technologic hazards.

PREFACE

A panel of internationally and nationally prominent seismologists, earthquake engineers, and earthquake policy experts met August 23-25, 1989, at Alta, Utah, to review Utah's earthquake problems and to provide the state legislature with an objective view about Utah's needs for earthquake-related instrumentation. This Utah Policy Panel on Earthquake Instrumentation was convened in response to a resolution filed by Representative Ray Nielsen—as part of a master study resolution (H.J.R. No. 34) at the end of the 1989 General Session of the Utah State Legislature—"to review the earthquake instrumentation needs of the state . . . and recommend actions in the 1990 annual session."

Legislative study of "Earthquake Instrumentation Needs of Utah," was assigned in March 1989 to the legislature's Interim Appropriations Committee in coordination with the Office of the Legislative Fiscal Analyst. To assist that committee and its legislative staff, leaders of Utah's state earthquake program (affiliated with the Utah Geological and Mineral Survey, the University of Utah Seismograph Stations, and the Utah Division of Comprehensive Emergency Management) assumed the responsibility: (1) for organizing a "blue-ribbon" panel of national experts to provide an objective, expert view of what earthquake instrumentation is genuinely needed and appropriate in Utah; and (2) for formulating a comprehensive briefing document for the panel.

The makeup and qualifications of the policy panel are outlined at the beginning of this report. A detailed, multipart briefing document was sent to the panel prior to the Alta meeting as a starting point for its deliberations at that meeting. The briefing document summarized what local experts in Utah considered to be the state's primary needs for earthquake-related instrumentation.

The excellent quality of the briefing document and the well-founded nature of its proposed plans drew a highly favorable response from the panelists. Indeed, with the notable exception of finding a proposed minimal plan for strong-motion instrumentation to be too conservative and sub-minimal, the panelists unanimously endorsed other proposed elements as representing a sound, "bare-bones" program for Utah. It is with this background that we proceed to report the valuable perspective and incisive recommendations of a truly formidable group of earthquake specialists. We thank them for their generous service to the State of Utah.

Alta, Utah	Senator Craig A. Peterson (Co-Chairman)
August 1989	(Former) Representative Jack Redd (Co-Chairman)

CONCLUSIONS AND RECOMMENDATIONS

Utah faces a serious threat of large damaging earthquakes. Consequences are all too vividly brought to mind by recent earthquake catastrophes in Armenia and Mexico City—both relevant examples for potential earthquake losses along Utah's Wasatch Front.

In dealing with its earthquake threat, Utah has a unique opportunity to "do it right." There are evident strengths in Utah's earthquake program, which involves uncommon and praiseworthy interagency cooperation. The possibilities for dealing with earthquake problems in Utah in an integrated and manageable way are enviable. Further, an instrumentation program has been proposed that, despite its modest scale, is unusually comprehensive and would place Utah's earthquake program at the forefront of the nation.

It should be clear at the outset that the proposed and recommended instrumentation program is not a menu of everything that could be done. Careful thought has been given to what Utah should have relative to its needs and means—and how to build on the strengths of Utah's existing program. What other states have is not the guideline. It should also be emphasized that instrumentation is an essential foundation that forms only part of a larger overall strategy for dealing with earthquake problems. Another necessary part is a commitment by the State to action and to policy changes for hazard reduction.

Is Utah's instrumentation program headed in the right direction? Emphatically yes. The plans presented to the panel were well-conceived and technically sound, and we judged them to reflect a conservative, "bare-bones" approach. In the area of strong-motion instrumentation, we found the minimal program that was originally proposed in fact to be sub-minimal and inadequate. The strong-motion program we recommend is intermediate between the minimal and optimal programs originally proposed.

There are compelling reasons for acquiring strong-motion information in Utah for earthquake engineering, and the information must be from Utah—not extrapolated from California. Existing construction in Utah is particularly vulnerable to earthquake damage. Studies by the Applied Technology Council indicate that for the same level of ground shaking, resulting damage in Utah will be 20 to 40 percent greater than in California. Much remains to be learned about the seismic response of unconsolidated valley fill that underlies most of the Wasatch Front urban corridor. An anomalously high percentage of Utah's population and gross state product is concentrated in this seismically dangerous area.

The instrumentation program that we recommend (described below) is a balanced, purposeful, and carefully crafted package. In the words of one of our panelists, "It's a whole midget." We support the *integrated* program; it should not be dismembered. Importantly, the package incorporates revolutionary technology in various aspects of the instrumentation that makes Utah's existing 1960- and 1970-era instrumentation outmoded and inadequate for modern engineering and science. The revolution in seismic instrumentation has crossed a threshold such that the proposed instrumentation will not be outmoded in the next 5 to 10 years. And the resulting high-quality data will never be obsolete.

Is the capital investment we recommend a good one? We say yes for a number of reasons. Modern technology and resulting information can indeed increase seismic safety. From the viewpoint of crisis management, Utah's earthquake threat involves high-consequence, low-probability events, and the instrumentation provides necessary and appropriate tools for guiding the management of risk, response, and recovery. It is estimated that state and local governments will have to absorb up to 75 percent of the total economic losses from a large earthquake in the U.S. According to the U.S. Geological Survey, a magnitude 7.5 earthquake on a central part of the Wasatch fault could result in damage losses to buildings alone exceeding $ 4.5 billion in Davis, Salt Lake, Utah, and Weber counties. This may represent only 20 percent of the total economic loss.

Our strategy in recommending that the State of Utah fund the proposed instrumentation package is as follows. First, we judge that the federal government will not simply provide the core funding. Reaganomics and stagnant federal support for earthquake programs virtually demand state involvement, and appropriately so. Second, we believe that the proposed package will provide a solid infrastructure that can be built upon. We are confident that the recommended state funds will be leveraged to attract significant federal and private funding. (University of Utah seismologists currently attract two federal dollars for every state dollar contributed.) Besides attracting other funding for program growth, the instrumentation program will attract top people who will be useful to Utah for other reasons. Within the realm of science and engineering, good high-quality data unquestionably generate great interest.

In addition to greater earthquake safety and reduced vulnerability to earthquake losses, other benefits to Utah could include potentially large savings and earnings. This includes insurance savings and savings from properly designing structures for earthquakes. Earthquake-resistant design is necessary in order to safeguard the investment made in any construction project. On the other hand, over-design can result in unnecessary spending, which can amount to millions of dollars for a single large project. Potential earnings will come not only from the attraction of more external funding to Utah's earthquake program, but also from increased willingness on the part of risk-conscious investors to fund large projects in Utah once the earthquake threat and the means to cope with it are better understood.

RECOMMENDATION 1.

We unanimously recommend to the Utah legislature a minimal, integrated 5-point program for earthquake instrumentation that will make Utah a better, safer place to live and work. Funding totaling $ 2.69 million (one-time) and $ 382,000/yr (ongoing) is recommended for the following elements:

A. Modernizing Seismic-Network Instrumentation

The proposed plan is designed to modernize the obsolete network of seismographic stations and central-recording facilities operated by the University of Utah Seismograph Stations for the purpose of identifying earthquake activity, better understanding and characterizing Utah's earthquake threat, and providing timely information for emergency response. Funding is recommended to replace computers, expand access to the State of Utah microwave system, upgrade a subset of existing seismic stations to modern three-component broadband digital operation, add new single-component digital stations along the Wasatch Front, and add new three-component regional stations off the Wasatch Front. It is also recommended that a satellite link be eventually established to interface the Utah seismic network with the U.S. National Seismic Network, but it is assumed that funding for this link will be provided by the U.S. Geological Survey.

To the University of Utah Seismograph Stations:

One-time cost — $ 673,000

Ongoing cost — $ 190,000/yr (includes 2.0 FTE @ $ 100,000 plus $ 90,000 for current/capital expense)

B. Strong-Motion Instrumentation for Earthquake Engineering

The proposed plan is designed to provide information specific to Utah about: (1) strong ground shaking close to large earthquakes, (2) the rate of decrease of strong ground shaking with distance, (3) amplification of ground motion due to local conditions, (4) threshold conditions for soil liquefaction, and (5) the effects of earthquakes on buildings and other structures. Funding is recommended for acquiring, deploying, and maintaining approximately 110 pieces of equipment. It is expected that at least 100 free-field sites (located away from structures), eight buildings, and one site for liquefaction studies will be instrumented.

The selection of priorities for sites and the mix of equipment for scientific and engineering purposes will be determined by a volunteer technical advisory panel consisting of representatives from the local geological, engineering, and construction communities as well as from universities and government agencies. Costs for the initial acquisition of equipment and its deployment by contracted specialists are included in the one-time cost. Funding for additional personnel and equipment will be solicited from federal and private sources.

California's successful strong-motion program is administered by the state geological survey (equivalent to the Utah Geological and Mineral Survey). Utah's program needs to be centered within a state entity that has relatively stable funding, a mission consistent with long-term scientific/engineering data collection associated with earthquake hazards, an administrator committed to the program, and a willingness to share data and promote effective communication among governmental entities, scientists, and engineers. More than one state entity in Utah could meet these qualifications.

One-time cost — $ 1,600,000
Ongoing cost — $ 120,000/yr (2.0 FTE @ $ 100,000, plus $ 20,000 current/capital expense)

C. Portable Seismographs for Strategic Data Collection

The proposed plan is designed to capture high-quality data from both ongoing background seismicity and aftershock sequences following moderate-to-large earthquakes in Utah. The data will be used by engineers, researchers, and others for better understanding earthquake hazards, for assessing risk, and for establishing design criteria. These versatile, portable instruments can be deployed and established soon after an earthquake to supplement the fixed regional network. They represent a cost-effective data-collection strategy, motivated by the limited number and inadequate distribution of regional network stations (even after the modest expansion described under Element A is completed). Funding will provide for acquisition of off-the-shelf, portable digital seismographs, together with a mixture of three-component broadband and short-period sensors and accessory equipment for rugged field conditions.

To the University of Utah Seismograph Stations:

One-time cost — $ 160,000
Ongoing cost — $ 22,000/yr (for current/capital expense)

D. Communication Systems for Information Transfer

The proposed plan provides for rapid transfer of earthquake information to emergency management personnel, other state and local officials, the news media, and the general public. The funding will provide for installation of an automated notification system, a dedicated mini-computer at the "hardened" emergency operation center of the Utah Division of Comprehensive Emergency Management (for access to automated earthquake locations and for back-up recording of earthquake data), and installation of a secure, direct radio link between key parties involved in emergency earthquake response.

To the Utah Division of Comprehensive Emergency Management:

One-time cost — $ 85,000
Ongoing cost — $ 10,000/yr (for current expense)

E. Earthquake Deformation Monitoring from Global Positioning Satellite Measurements

The proposed plan will establish baseline data for monitoring crustal deformation that may signal an impending earthquake. At the same time, it will make GPS-surveying instruments available to local governments for other uses. Geodetic measurements establish pre- and post-seismic ground deformation and can be used to evaluate areas vulnerable to potentially disastrous inundation that may accompany large surface-faulting earthquakes on the Wasatch fault. Recommended one-time funding includes $103,000 for three GPS receivers and accessory equipment for making precise satellite-based positioning measurements. The cost for the GPS receivers assumes their acquisition through UNAVCO—the University NAVSTAR CONSORTIUM sponsored by the National Science Foundation—at a substantial reduction. The consortium requires that such instruments be owned by a university, and we suggest that these funds be allocated to the University of Utah, a member of the UNAVCO consortium. The one-time cost also includes $ 65,000 for our recommended acquisition of a computer-based "Total Station"—a state-of-the-art electronic distance-measuring and positioning device (and accessory equipment) that will be extremely valuable for precise, small-scale geological and engineering studies relating to various aspects of earthquake deformation.

We recommend that the State of Utah take opportune advantage of an offer extended by the National Geodetic Survey to share (50-50) the salary of an NGS/State geodetic advisor, who would reside in Utah, for ensuring the effective utilization of the GPS instrumentation and for promoting ties among the state scientific, engineering, and surveying communities. Logically, the ongoing funding would go to an entity within the University of Utah.

One-time cost — $ 168,000
Ongoing cost — $ 40,000/yr (including 0.5 FTE and $10,000 current expense)

RECOMMENDATION 2.

We recommend continued close cooperation among the University of Utah Seismograph Stations, the Utah Geological and Mineral Survey, and the Utah Division of Comprehensive Emergency Management. The success of this instrumentation initiative will require exceptionally close coordination between the proposed strong-motion program and the seismological program. The five elements of this earthquake instrumentation program should not be viewed as separate and distinct. Every effort should be made to promote coordination so that capital outlays being made for earthquake instrumentation for the respective elements will result in a unified information-gathering program in Utah—for engineering, research, and emergency-management needs.

RECOMMENDATION 3.

We recommend that ongoing cooperative agreements with federal agencies such as the U.S. Geological Survey be used as a basis for promoting specific assistance that will be advantageous to this instrumentation initiative. There will be a need for technical personnel to implement and ensure effective use of the proposed earthquake instrumentation. As part of the existing state-federal partnership, the USGS should be urged (1) to provide personnel for assisting development of the proposed strong-motion program and (2) to assign an earthquake seismologist to work with the University of Utah seismology group in advanced research using new high-quality data that will result from this initiative. Further, the USGS should be urged to give high priority to establishing a satellite link between the recording center of the University of Utah Seismograph Stations and the master station (in Golden, Colorado) of the currently evolving U.S. National Seismic Network.

Earthquake Instrumentation for Utah

A Briefing Paper
for
Utah Policy Panel on Earthquake Instrumentation

August 17, 1989

(Revised October 17, 1989)

Ed. Note: As reproduced here, this multipart briefing paper is mostly the same (with exceptions described below) as that presented to members of the Utah Policy Panel on Earthquake Instrumentation prior to their meeting August 23-25, 1989, at Alta, Utah. The purpose of the briefing paper was to serve as a starting point for the deliberations of the policy panel—and it was intended to summarize what local experts in Utah considered to be the state's primary needs for earthquake-related instrumentation.

As a result of changes recommended by the policy panel, that part of the instrumentation initiative dealing with strong-motion instrumentation was modified substantially. A revised description of "Element B—Strong-Motion Instrumentation for Earthquake Engineering" is included in this package incorporating all changes recommended by the panel. Correspondingly, the "Executive Summary" has been annotated and revised to account for the changes. All other parts of the briefing paper are original versions.
—WJA

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Contents

ATTACHMENTS: (These attachments not included in this package.)

1. Atwood, G. and W.J. Arabasz (July 1989). *An Initiative to the Utah State Legislature to Address State Needs for Earthquake-Related Instrumentation* (an overview of the rationale, background, and developments relating to this instrumentation initiative, 5p.)
2. *Utah Economic and Business Review v. 49, no. 3 (March 1989 issue)*
3. *Reducing Losses from the Physical Effects of Earthquakes Expected in Utah* (July 1989). (A consensus view of scientists, engineers, planners, emergency management officials and others involved in a five-year program, 1983-1988, sponsored by the National Earthquake Hazards Reduction Program and focused on earthquake hazards and risk in Utah, 19 p.)
4. Arabasz, W.J., J.C. Pechmann, and E.D. Brown (1989). *Observational Seismology and the Evaluation of Earthquake Hazards and Risk in the Wasatch Front Area, Utah* (Hays, W.W. and P.L. Gori, eds., U.S. Geological Survey Professional Paper, in press).
5. Machette, M.N., S.F. Personius, A.R. Nelson, D.P. Schwartz, and W.R. Lund (1989). *Segmentation Models and Holocene Movement History of the Wasatch Fault Zone, Utah* (U.S. Geological Survey Open-File Report 89-315, pp. 229-245).
6. University of Utah Seismograph Stations (August 1989). *The University of Utah Seismograph Stations and Seismology Research Group—An Overview*

7. Madsen, G.E., L.R. Anderson, J.H. Barnes, and C. Nelson (1989). *Earthquake Risk and Defensive Policies as Perceived by Community Leaders and the Public* (preprint).

8. Heaton, T.H., D.L. Anderson, W.J. Arabasz, R. Buland, W.L. Ellsworth, S.H. Hartzell, T. Lay, and P. Spudich (1989). *National Seismic System Science Plan* (U.S. Geological Survey Circular 1031, 42 p.)

9. Doser, D.I. and R.B. Smith (1989). *An Assessment of Source Parameters of Earthquakes in the Cordillera of the Western United States* (Bulletin of the Seismological Society of America, in press)

10. Benz, H.M. and R.B. Smith (1988). *Elastic-Wave Propagation and Site Amplification in the Salt Lake Valley, Utah, from Simulated Normal Faulting Earthquakes* (Bulletin of the Seismological Society of America, v. 78, no. 6, pp. 1851-1874).

11. Richins, W.D., J.C. Pechmann, R.B. Smith, C.J. Langer, S.K. Goter, J.E. Zollweg, and J.J. King (1987). *The 1983 Borah Peak, Idaho, Earthquake and Its Aftershocks* (Bulletin of the Seismological Society of America, v. 77, no. 3, pp. 694-723).

12. Westaway, R. and R.B. Smith (1989). *Strong Ground Motion in Normal-Faulting Earthquakes* (Geophysical Journal, v. 96, pp. 529-559).

EXECUTIVE SUMMARY

This briefing paper for the Utah Policy Panel on Earthquake Instrumentation has six separate parts—an introduction and five proposed plans. Each plan, written by a working group of local experts involved in Utah's earthquake program, addresses an element of what are judged to be Utah's primary needs for earthquake-related instrumentation. Together, the plans provide a starting point for joint deliberations by the panel about what instrumentation is really needed and appropriate in Utah for effective earthquake hazard reduction.

A Synopsis of Each Part

Introduction, Background Information, and Perspective

[(1) Describes the panel's charge; (2) provides background information (facts and figures about Utah's economy, specifics about the earthquake threat in Utah, an overview of Utah's state earthquake program); and (3) presents a perspective on the challenge of lessening the earthquake threat in Utah.]

Element A. Modernizing Seismic-Network Instrumentation

Existing seismic-network facilities in Utah for the recording and study of earthquakes are technologically outdated, unreliable because of aging, and argued to be fundamentally inadequate to meet important needs for public safety, basic research, and engineering applications.

A multi-part instrumentation plan is proposed for modernizing a network of 55 seismographic stations and central-recording facilities in Utah operated by the University of Utah Seismograph Stations. The proposed plan involves the following parts (for which one-time and recurring costs for acquiring and maintaining the instrumentation are listed—with personnel requirements summarized in a separate later section):

- Replacement of two computers dedicated to specialized functions of the Seismograph Stations' central-recording and data-processing laboratory. (Both computers are 1970's vintage, have been in service since 1980, and are now technologically inadequate and obsolete.) One-time instrumentation costs = $272K; recurring hardware maintenance costs = $22K.

- Expanded access to State of Utah microwave system—for establishing a cost-effective infrastructure for evolutionary development of a modern, statewide digital seismic network. Establishing a node of the state microwave system on the University of Utah campus could cost as much as $75K (possibly justified or cost-shared in connection with other University/State needs). The campus drop-off would eliminate future recurring costs of about $40K/yr for commercial telephone circuits to carry seismic telemetry channels from the nearest existing microwave drop-off to the University campus only five miles away. (The $40K/yr assumes an increase from 6 currently used channels to 24 channels.) Additional one-time costs for acquiring 18 more microwave channels on the state system would be about $8K; recurring usage charges for those 18 channels would be about $30K/yr—unless the state could be persuaded to reduce its service charges.

- Upgrading of 10 existing seismic stations to three-component broadband digital operation—technologically essential for acquiring critically-needed data for engineering applications and basic research. One-time costs = $240K; recurring costs = $21K/yr (assuming rule-of-thumb of 10 percent x hardware costs).

- Addition of 10 new single-component stations along the Wasatch fault using existing sensors and new digital telemetry. (Station spacing along the Wasatch Front now allows reliable focal-depth resolution for fewer than 10 percent of the located earthquakes.) One-time equipment costs = $36K; recurring costs = $4K/yr (using 10-percent rule; microwave start-up and usage charges included in earlier sum).

- Addition of 7 new three-component regional stations—to expand seismographic coverage of seismically active, but inadequately instrumented parts of Utah. (Involves moving existing equipment that will become available from conversion of other stations to broadband digital operation.) One-time costs = $42K (for high-quality station siting); recurring costs = $4K (microwave start-up and usage charges included in earlier sum).

- Eventual upgrading of 7 regional stations (described in the preceding part) from three-component analog operation to digital telemetry, plus replacement of seismometers with modern broadband sensors. One-time costs = $122K; recurring costs = $22K (using the 10 percent-rule and adding $10K/yr for added microwave channels not accounted for earlier). (*Note: It is assumed that funding for this eventual upgrading might come from future federal support. These costs are not included in the proposed total for Element A.*)

- Establishing a satellite link for interfacing the University of Utah's regional recording center with a master station of the planned U.S. National Seismic Network (USNSN) in Golden, Colorado. A national program to integrate regional seismic networks with the USNSN will eventually involve the installation of three high-quality USNSN stations in Utah, at an estimated cost of $50K/station, plus the completion of a satellite link at key regional recording centers, such as at the University of Utah, at a cost of about $35K-45K. *(It is assumed that funding for these developments will ultimately be provided by the U.S. Geological Survey if and when federal dollars become available for completing the entire USNSN project. These costs are not included in the proposed total for Element A)*

Total One-Time Costs for Element A = $ 673K

Total Recurring Costs for Element A = $ 81K/yr

Element B. Strong-Motion Instrumentation for Earthquake Engineering (ORIGINAL VERSION)

Ed. Note: This summary is the one from the ORIGINAL briefing paper. A revised summary for the strong-motion program subsequently recommended by the policy panel then follows. —WJA

Engineers need accurate predictions of strong ground motion during future earthquakes in Utah in order to design buildings and other structures to withstand these earthquakes. The ability of seismologists and engineers to make such predictions is currently hampered by the lack of free-field recordings of strong ground motion from past earthquakes in the state. In order to obtain such records from the next large ($M \geq 6.5$), surface-faulting earthquake in Utah, it is necessary to expand the current network of strong-motion accelerographs, which includes instruments at only 25 different recording sites.

At the minimum, it is proposed that 23 new accelerographs be purchased and installed. These 23 accelerographs, together with existing accelerographs, will enable quantitative measurements of strong ground shaking from the next large surface-faulting earthquake in Utah at a minimum of two free-field sites within 10 km of the fault (one located on bedrock and the other located on unconsolidated deposits). An "optimal" plan is also proposed for consideration that would enable the collection of a definitive data set on strong ground motions from the next large, surface-faulting earthquake, consisting of free-field recordings from at least 18 different sites. The optimal plan would require the installation of accelerographs at 255 new free-field sites. The optimal program also provides for the installation of accelerograph systems in ten buildings in Utah to obtain engineering data on the structural response of these buildings to earthquakes.

Total One-Time Costs for Element B, Minimal Plan: $ 268,000

Total Recurring Costs for Element B, Minimal Plan: $ 16,100/yr

Total One-Time Costs for Element B, Optimal Plan: $ 3,580,000

Total Recurring Costs for Element B, Optimal Plan: $ 200,000/yr

Element B. Strong-Motion Instrumentation for Earthquake Engineering (REVISED VERSION)

Engineers need accurate predictions of strong ground motion during future earthquakes in Utah in order to design buildings and other structures to withstand these earthquakes. The ability of seismologists and engineers to make such predictions is currently hampered by the lack of free-field recordings of strong ground motion from past earthquakes in the state. In order to obtain such records from the next large ($M \geq 6.5$), surface-faulting earthquake in Utah, it is necessary to expand the current network of strong-motion accelerographs, which includes instruments at only 25 different recording sites.

It is proposed that a strong motion instrumentation program be established for the State of Utah with the following five elements: (1) a volunteer advisory panel to provide technical advice and guidance for the program, (2) operation of the program by the Utah Geological and Mineral Survey, (3) one-time capital funds of $1.6 million to purchase and install instruments, (4) ongoing funding to support instrument maintenance, collection and analysis of data, and, if possible, procurement of additional instruments, and (5) supplemental funds from private sources and federal agencies for purchase of additional instruments. The one-time capital funds would provide for the purchase and installation of: (1) accelerographs at 100 new free-field sites in Utah to collect data on ground motions, (2) accelerograph systems in 8 buildings to collect data on the structural response of these buildings to earthquakes, and (3) a set of instruments to study soil liquifaction.

Total One-Time Costs for Element B: $ 1,600,000

Total Recurring Costs for Element B: $ 120,000/yr

Element C. Portable Seismographs for Strategic Data Collection

Supplementing a fixed regional seismic network with versatile portable seismographs is a fundamental, cost-effective data-collection strategy of earthquake seismology. This strategy is particularly important in Utah because of the inadequate number and distribution of regional-network stations. This plan proposes the acquisition of 10 off-the-shelf portable digital seismographs (5 PASSCAL seismographs and 5 lower-cost instruments), together with a mixture of three-component broadband and short-period sensors, and accessory equipment for rugged field conditions. The purpose is to acquire high-quality portable-array data—from the recording both of background seismicity and aftershock sequences—for earthquake hazard and risk assessments, for defensive earthquake engineering, and for basic research.

Total One-Time Costs for Element C: $ 159,275

Total Recurring Costs for Element C: $ 22,000/yr

Element D. Communications Systems for Information Transfer

Existing communication systems in Utah for the rapid transfer of earthquake information—to emergency management personnel, the news media, and the general public—are too vulnerable to disruption, too dependent on the availability and intervention of key personnel, and take little to no advantage of existing technology for automated and rapid information transfer.

The plan for this element proposes: (1) installation of an automated notification system, based of current technology, to provide near-real time information on earthquake parameters; (2) installation of a mini-computer at a "hardened" emergency operation center of the Utah Division of Comprehensive Emergency Management for backup recording of earthquake data; and (3) installation of a secure, direct radio link between key parties involved in emergency earthquake response.

Total One-Time Costs for Element D: $ 84,103

Total Recurring Costs for Element D: $ 9,458/yr

Element E. Earthquake Deformation Monitoring from Global Positioning Satellite Measurements

Geodetic measurements in Utah, especially along the Wasatch fault and other active faults, are urgently needed to establish baseline data for monitoring crustal deformation that may signal an impending earthquake. Geodetic measurements are necessary to establish pre- and postseismic ground deformation and to evaluate areas vulnerable to potentially disastrous inundation (such as from the Great Salt Lake or Utah Lake) that may accompany large surface-faulting earthquakes on the Wasatch fault.

This plan proposes that the state of Utah acquire three portable Global Positioning System (GPS) receivers for (1) making precise satellite-based positioning measurements of crustal deformation and (2) serving (simultaneously) the needs of the state engineering community for statewide surveying and mapping. GPS technology offers a unique opportunity for meeting multi-agency needs in any state. The National Geodetic Survey is trying to encourage state participation in geodetic control networks and would provide up to half the salary of an NGS-State geodetic advisor residing in Utah.

Ed. Note: The following two lines of summary costs are those that appeared in the original briefing paper. —WJA

Total One-Time Costs for Element E = $ 155K-185K

Total Recurring Costs for Element E = ~$ 25K-30K/yr

As revised and recommended by the Utah Policy Panel on Earthquake Instrumentation, the summary costs are as follows. (The revised estimated one-time costs include: (1) $103,000 for three GPS receivers and accessory equipment at a special price available through UNAVCO—the University NAVSTAR CONSORTIUM sponsored by the National Science Foundation; and (2) $65,000 for a computer-based "Total Station"—a state-of-the-art electronic distance-measuring and positioning device for precise, small-scale geological and engineering studies relating to various aspects of earthquake deformation.

Total One-Time Costs for Element E = $ 168,000

Total Recurring Costs for Element E = $ 40,000

The Issue of Personnel and Other Recurring Costs

Installation and effective use of the proposed instrumentation will unquestionably require significant personnel efforts from technical specialists, seismologists, and engineers. And recurring costs for the maintenance and repair of instrumentation, together with costs for necessary supplies, are inescapable. Reviewing the plans for the respective elements—and mindful of the need to be conservative when considering staffing increases—we make the following comments:

- Elements A (network modernization) and C (portable seismographs) combined can only be handled by the University of Utah Seismograph Stations with additional personnel. Multi-year implementation of the instrumentation plans is assumed. Plans for the computer replacements envision "turnkey" installations, but realistically a computer specialist will be needed on a full-time basis for about 6 months. The network upgrading and expansion will require one additional engineer/technician on a permanent basis, and a supporting field technician for a front-end two-year period.

(Currently, the Seismograph Stations' field/electronics staff includes one engineer and one electronics technician.)

- The cost structure for Element B (strong-motion program) has been developed in such a way that costs for installation and maintenance of instruments include an average cost per station for manpower and supplies. Because the shape and form of a strong-motion program for Utah is highly uncertain at this point, we leave the personnel issue for future discussion with the panel. It seems apparent, however, that Utah's state earthquake program has a compelling need for an engineering seismologist. One possible scenario is the addition of such a seismologist to the research faculty at the University of Utah—perhaps with full funding, say, for an initial one- or two-year period followed by half-time funding (with the remaining half-time to be secured from research awards). (Currently, the state of Utah provides only 48 percent of the annual salary for Dr. W.J. Arabasz, director of the University of Utah Seismograph Stations, and 35 percent of the annual salary for Dr. J.C. Pechmann, Research Associate Professor and a key seismologist in Utah's earthquake program. In both of the latter cases, remaining salary support comes from competitive research awards.)

- Personnel efforts for implementation of Element D (communication systems) can basically be handled by existing staff of the University of Seismograph Stations and the Utah Division of Comprehensive Emergency Management.

- The plan for Element E (GPS monitoring) describes a willingness by the National Geodetic Survey to provide up to half the salary of an NGS-State geodetic advisor residing in Utah. Given the prospects for multi-agency interest in, and benefit from, a GPS monitoring program in Utah, such an offer seems to be extremely attractive in terms of promoting a coherent state approach to meeting state needs for both surveying and geodetic monitoring. It is assumed at this point that operational costs for use of the GPS portable receivers can be handled as part of the routine operations of various state agencies involved in surveying.

- We believe it goes without saying that recurring costs for the maintenance and repair of modern electronic instrumentation must be anticipated and provided for. Industry guidelines and experience suggest that such costs, on an annual basis, will amount to roughly 10 percent of the initial capital cost of the instrumentation.

Ed. Note: The following four lines of summary costs are those that appeared in the original briefing paper. —WJA

Total One-Time Personnel Costs: ~$ 300K

Total Recurring Personnel Costs: ~$ 100K/yr

BOTTOM LINE ONE-TIME COSTS: ~$ 1.6-1.7 million

BOTTOM LINE RECURRING COSTS: ~$ 250K-260K/yr

As revised and recommended by the Utah Policy Panel on Earthquake Instrumentation, the summary costs are:

BOTTOM LINE ONE-TIME COSTS: $ 2,686,000

BOTTOM LINE RECURRING COSTS: $ 382,000/yr

An Afterword

This initiative to the Utah state legislature addresses fundamental needs of the state. The proposed instrumentation involves modern technology which so surpasses outmoded earthquake instrumentation in Utah, that the state's earthquake program is truly at a crossroads. We believe that continuing the status quo in terms of the state's earthquake instrumentation is no longer a responsible option.

As a final perspective, $15 million in federal funds was reportedly spent under the National Earthquake Hazards Reduction Program during the 1983-88 focus on Utah's Wasatch Front. (Of the $15 million, capital spending on instrumentation included only $21K to the University of Utah Seismograph Stations for seismic-network instrumentation and an unknown amount [perhaps of the order of $150K] for USGS deployment of strong-motion instruments in Utah.) Great resources have been applied to defining and quantifying the earthquake threat in Utah. But accurate technical information will continue to be critical for dealing with that threat. We submit that the costs for Utah's needed earthquake instrumentation are not inordinate.

Introduction, Background Information, and Perspective

by Walter J. Arabasz and Genevieve Atwood

> *When you must go to (the top) for assistance, don't go whining and complaining that you haven't got the resources you need . . . . Present a plan describing what has to be done and what you think is needed to accomplish the job.*
>
> *Personal Report for the Executive (Jan. 1988)*

THE AUTHORS

WALTER ARABASZ is Director of the University of Utah Seismograph Stations and a Research Professor in the University's Department of Geology and Geophysics. **GENEVIEVE ATWOOD** is Director of the Utah Geological and Mineral Survey.

Introduction

As early as 1883, the eminent geologist G.K. Gilbert recognized and warned of the serious earthquake threat posed by the Wasatch fault and other active faults in Utah—despite the absence up to that time of any large earthquakes in the region since settlement by Mormon pioneers in 1847. In modern times, scientists, engineers, planners, and emergency management offícals have amassed a large body of technical information quantifying Utah's earthquake hazards and risk. The box below gives an example of the current risk perspective.

Los Angeles Times: *Sunday, May 21, 1989 / Part VIII*

U.S. CITIES AT RISK FROM EARTHQUAKES

Estimates of the likelihood of an earthquake that will cause significant damage within 50 years and considers entire metropolitan area, taking into account building conditions and local geology.

City	Estimated Risk
Los Angeles	96 to 99%
San Francisco	30 to 85%
Salt Lake City (including nearby cities)	15 to 40%
Seattle	15 to 25%
St. Louis	3 to 15%
Denver	2 to 10%

SOURCES: David Perkins, U.S. Geological Survey; Roulac Real Estate Consulting Group of Deloitte Haskins & Sells

The Wasatch Front area is a classic example of a seismically active region having only moderate historical seismicity but high catastrophic potential from future large earthquakes. Devastation caused by the magnitude 6.9 earthquake in Armenia on December 7, 1988, gives a real-world lesson for such situations. The high death toll of at least 30,000 people in the Armenian earthquake, due primarily to the collapse of modern buildings, emphasizes the price for not heeding the threat of infrequent large earthquakes. According to Peter Yenev (an American earthquake engineering specialist), "Rarely has the importance of systematic risk identification and proper seismic design and construction in earthquake-prone areas been more apparent (than in the Armenian earthquake)" (*EPRI Journal*, June 1989, p. 24).

It is well established that the disastrous effects of earthquakes can be significantly lessened by proper siting and construction practices and by effective disaster-response planning. But these strategies critically depend upon accurate information—information that reliably characterizes and predicts the earthquake hazards beforehand and earthquake information that is rapidly transferred to emergency management officials when a destructive event occurs.

In a fundamental way, earthquake-related information is linked to instrumentation. Unfortunately, existing earthquake-related instrumentation in Utah is out-of-date and seriously inadequate for meeting the state's needs—for earthquake monitoring, hazard identification and mitigation, defensive engineering design, and emergency response and public safety. Given this situation, the quotation on the title page of this section provides an appropriate cue. The Utah Policy Panel on Earthquake Instrumentation is part of a process designed to "present a plan describing what has to be done and what . . . is needed to accomplish the job."

Charge to Panel and Overview of Instrumentation Initiative

You have been asked to provide Utah's state legislature with an independent, objective, and expert view about what earthquake-related instrumentation is really needed and appropriate in Utah for effective earthquake-hazard reduction. Panel recommendations should also include a rough estimation of justifiable costs and suggestions to the legislature for funding strategies.

Earlier, you reviewed a written overview of the rationale, background, and developments relating to this instrumentation initiative. To avoid repetition, that overview is included here as Attachment No. 1.

Outline of This Document

This briefing paper consists of six parts. First, this introductory part provides relevant background information and is intended to give you a basic understanding of the problem. Five separate parts then follow—each of which addresses an element of what are judged to be Utah's primary needs for earthquake-related instrumentation:

A. Modernizing Seismic-Network Instrumentation

B. Strong-Motion Instrumentation for Earthquake Engineering

C. Portable Seismographs for Strategic Data Collection

D. Communication Systems for Information Transfer

E. Earthquake Deformation Monitoring from Global Positioning Satellite Measurements

For each element listed above, a working group of local experts—with input from other knowledgeable experts—has outlined a proposed plan as a starting point for the panel's deliberations.

Judgment about "what's appropriate for Utah" (compared, for example, to California) naturally requires some familiarity with Utah's economic statistics. The following outline gives a thumbnail sketch. More detailed data are summarized in Attachment No. 2.

State Population:	1.7 million (1988)
Growth Rate:	15.7 percent per decade (currently the 9th fastest growing state in the U.S.)
Population Density:	Heavily influenced by physiography (Fig. 1) and by historical pattern of urban settlement along the Wasatch Front. More than 80% of Utah's population is concentrated within a few tens of kilometers of the Wasatch fault (Fig. 2). There are economically important facilities statewide, however (Fig. 3).
Number of Counties:	29 (see Fig. 4). Most populous county is Salt Lake County with 705,000 people in 1988.
State Budget:	$2.9 billion (1989-90 fiscal year)
Tax Base:	Total assessed valuation = $47.4 billion (1988)
Annual Construction:	$413 million (new residential construction, 1988) $272 million (new nonresidential construction, 1988) $847 million (total construction, including nonbuildings, 1988)

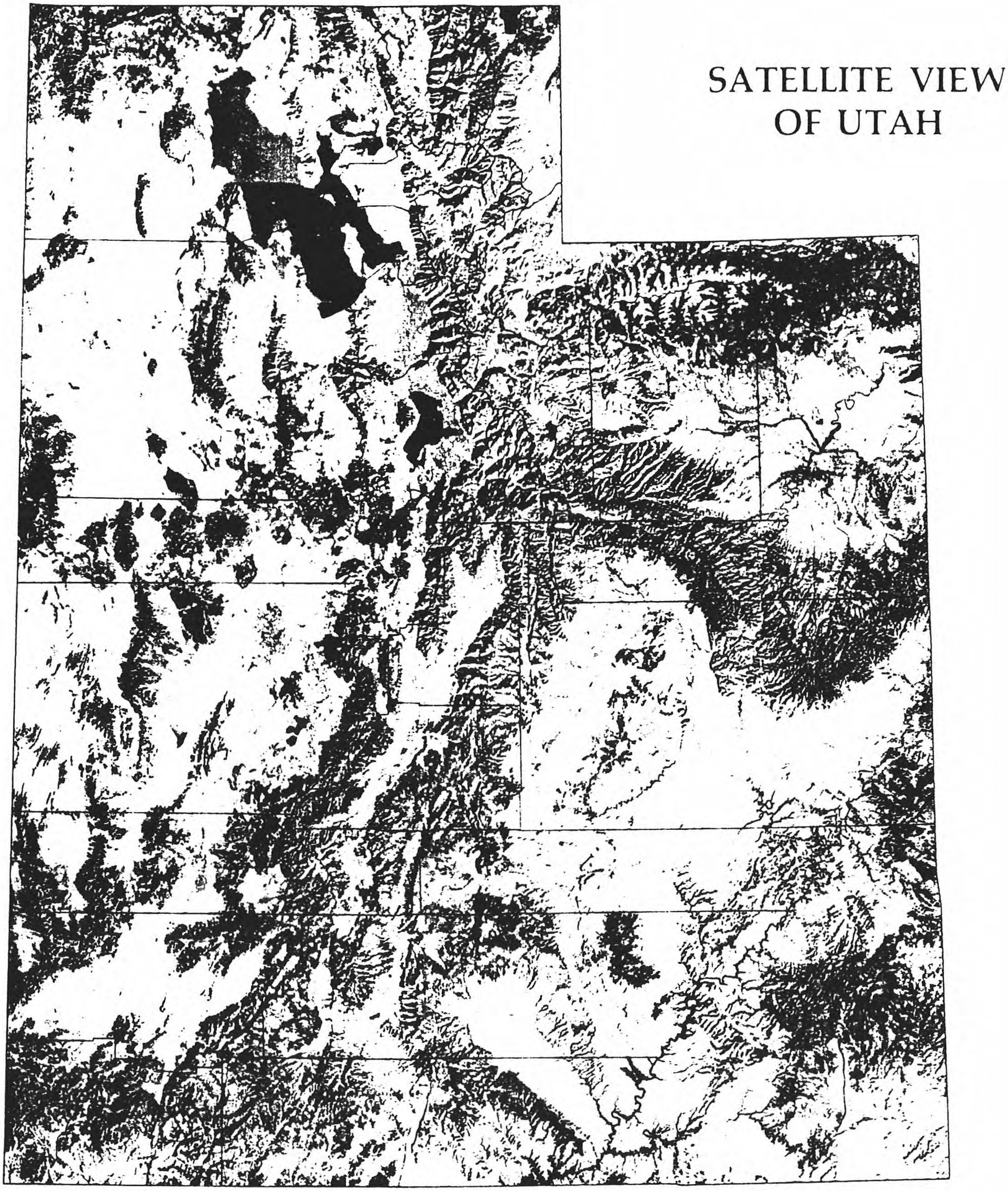


Figure 1.

(Reproduced from *Atlas of Utah*)

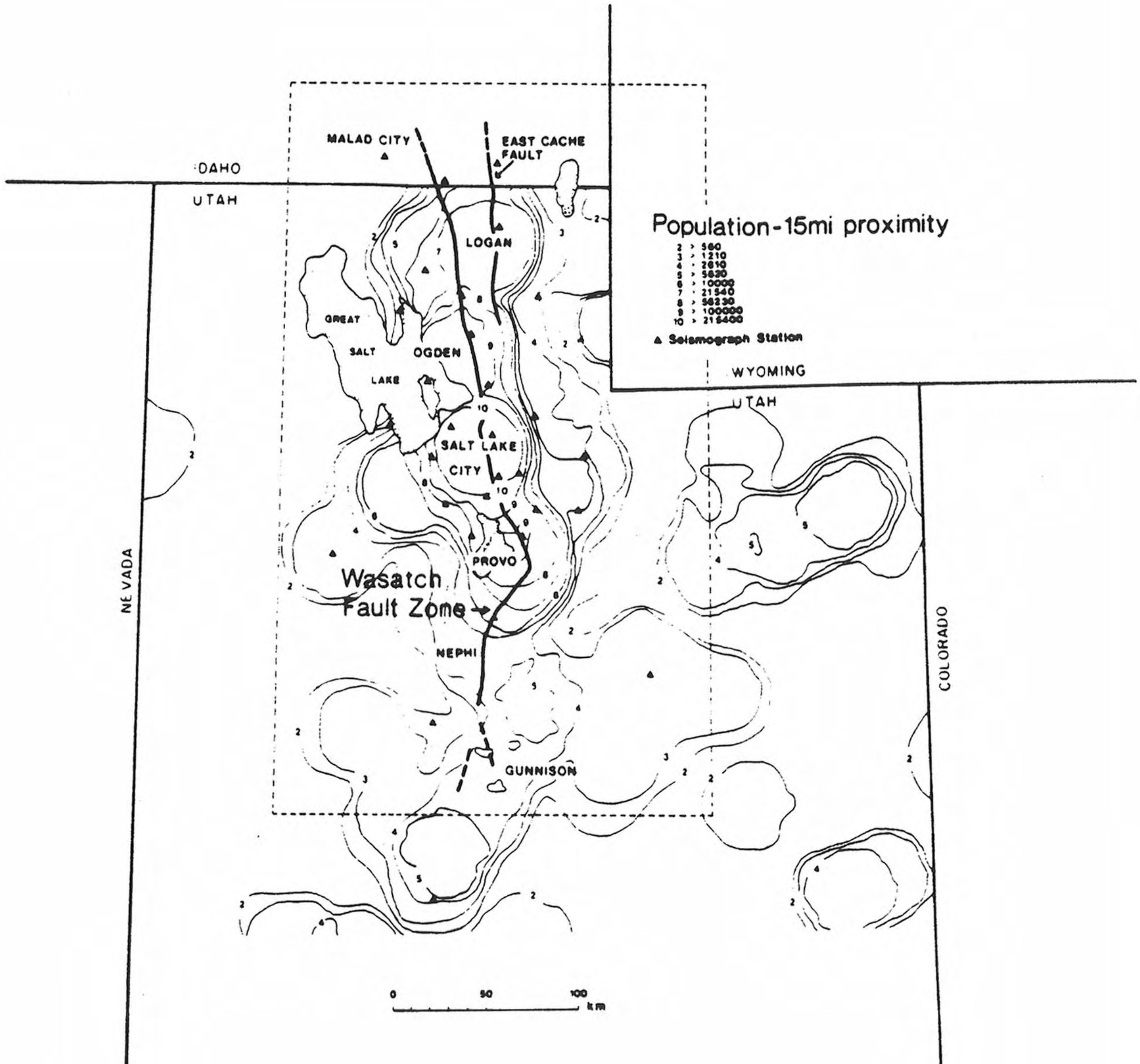
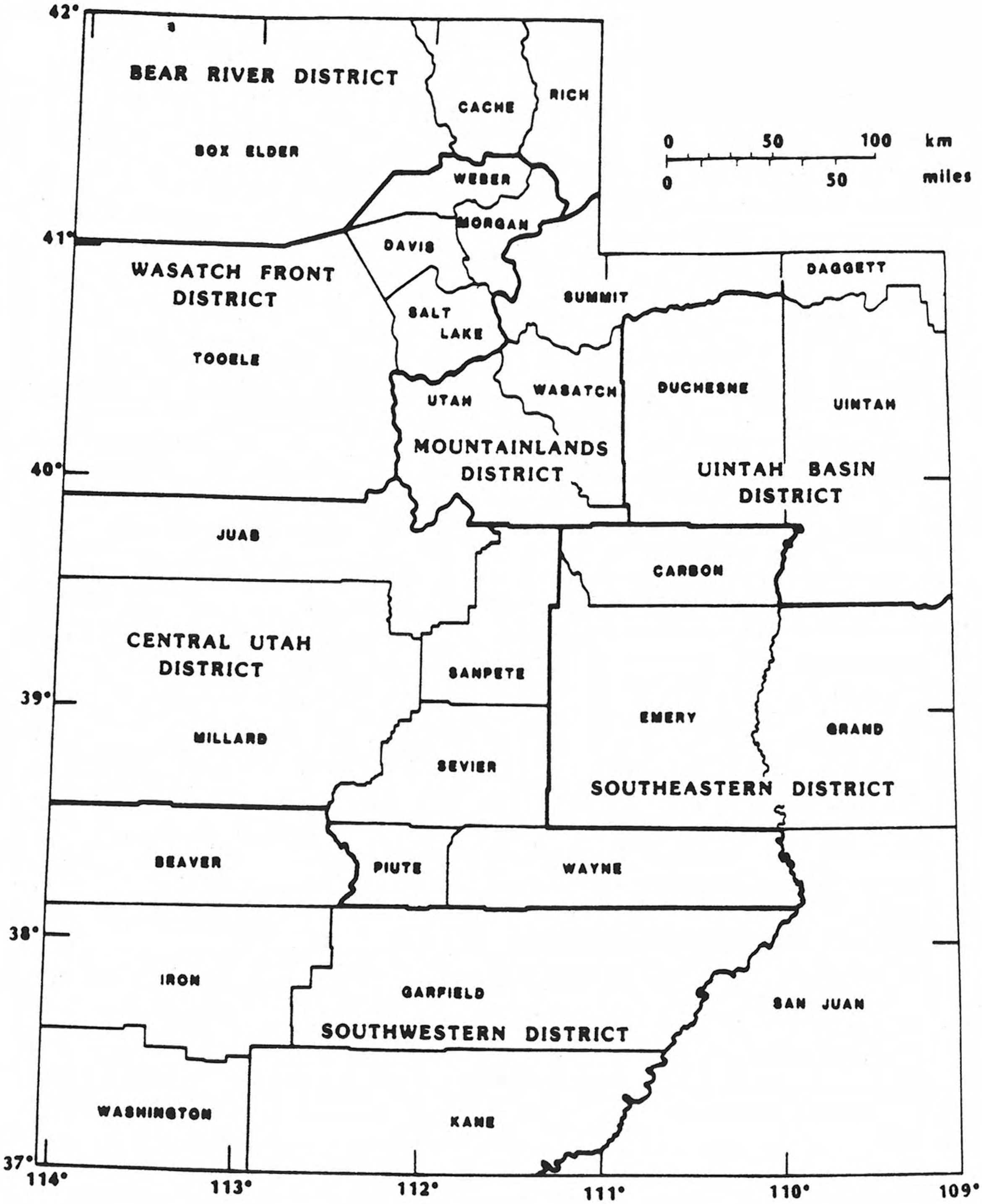


Figure 2.

Map of Wasatch Front area illustrating high population density in vicinity of major active faults. Contours of population from *Statistical Abstract of Utah, 1976*. (from Arabasz and others, 1979, *Earthquake Studies in Utah, 1850 to 1978*).



UTAH PLANNING DISTRICTS AND COUNTIES

Figure 3.

UTAH FAULTS, ENERGY AND MINERAL RESOURCES

(REFERENCE MAP)

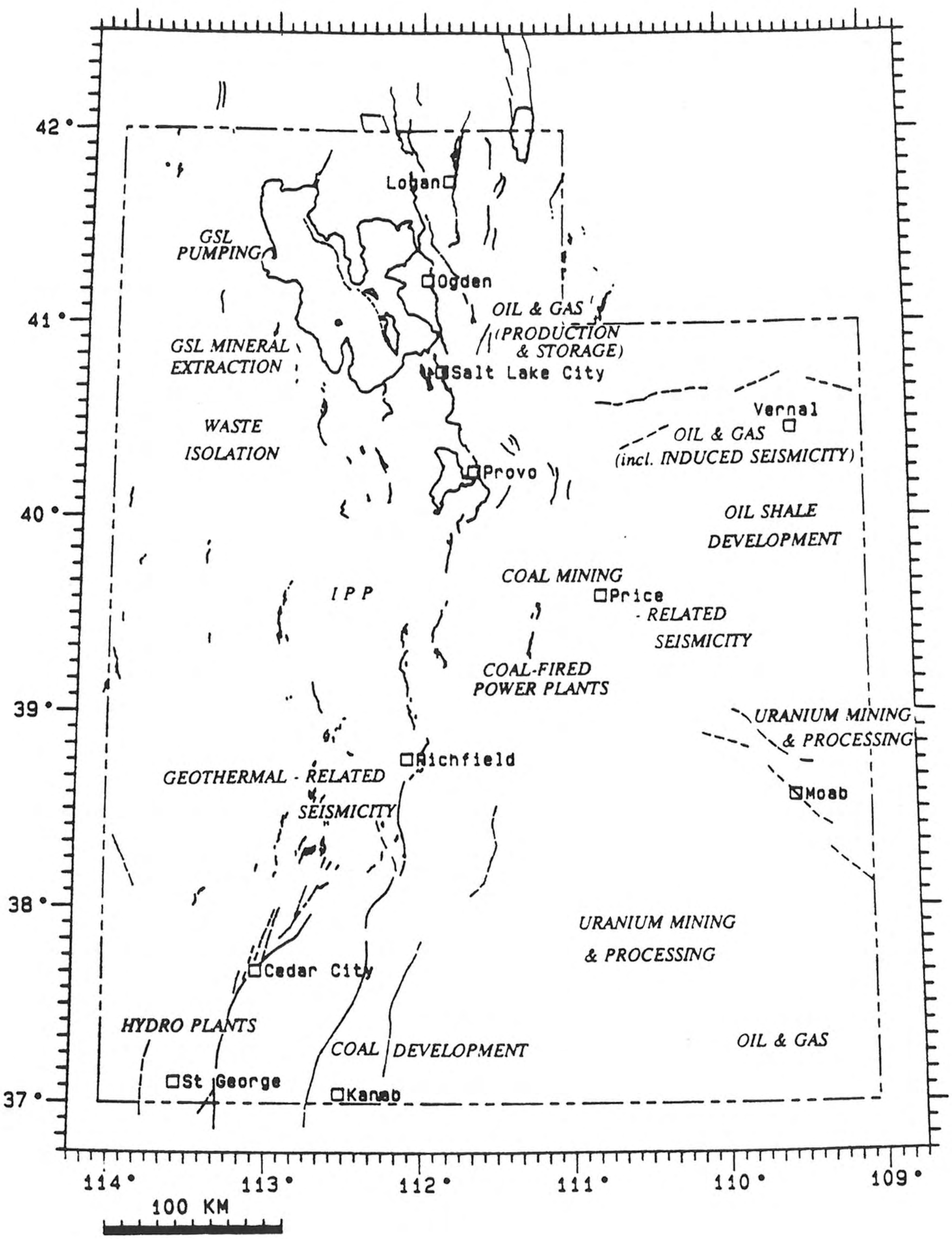


Figure 4.

Background Information—More on Utah's Earthquake Threat

Seismologists, geologists, and engineers have reached a fundamental consensus about technical details of the earthquake threat in Utah—where, how big, how often, and what's going to happen. That consensus, arrived at as part of a special five-year focus (1983-1988) on the Wasatch Front region under the National Earthquake Hazards Reduction Program, is articulated in a draft document included here as Attachment No. 3 (see Part 3, in particular, for technical details). Scientific perspectives from observational seismology and paleoseismology (the geological study of the age, frequency, and size of *prehistoric* earthquakes) are amplified in Attachment Nos. 4 and 5, respectively. Here are some relevant highlights:

Source and Frequency of Earthquakes

- Utah is transected by the Intermountain seismic belt (Fig. 5)—characterized by diffuse shallow seismicity, Holocene normal faulting, and high seismic risk associated with episodic surface-faulting earthquakes of magnitude 6.5 to 7.5+.

- Since 1850, at least 16 independent earthquakes (aftershocks excluded) of magnitude 6.0 or greater have occurred within the Intermountain seismic belt (Fig. 5). Three of these historical earthquakes were associated with documented surface faulting: (1) the magnitude 6.6 Hansel Valley, Utah, earthquake of 1934, (2) the magnitude 7.5 Hebgen Lake, Montana, earthquake of 1959, and (3) the magnitude 7.3 Borah Peak, Idaho, earthquake of 1983.

- The greatest threat for large surface-faulting earthquakes in the Utah region is posed by the 370-km-long Wasatch fault zone (Figs. 5 and 6)—despite the fact that it has not generated any earthquakes larger than magnitude 5 in historical time. (Large surface-faulting earthquakes can also occur on numerous other known active faults in Utah showing evidence of prehistoric surface rupture. In general, those other faults tend to have longer recurrence intervals for surface rupture.)

- The Wasatch fault is made up of as many as 12 independent fault-rupture segments (Fig. 6). Segments along the central two-thirds of the fault from Brigham City to Nephi have each ruptured two or more times in the past 6,000 years (Fig. 7).

- Geologic trenching and dating studies indicate that the pattern of timing of large surface-faulting earthquakes on the Wasatch fault during the past 6,000 years is complicated (Fig. 7). For the segments between Brigham City and Nephi, the *composite* recurrence interval—the average time between two faulting events anywhere on this

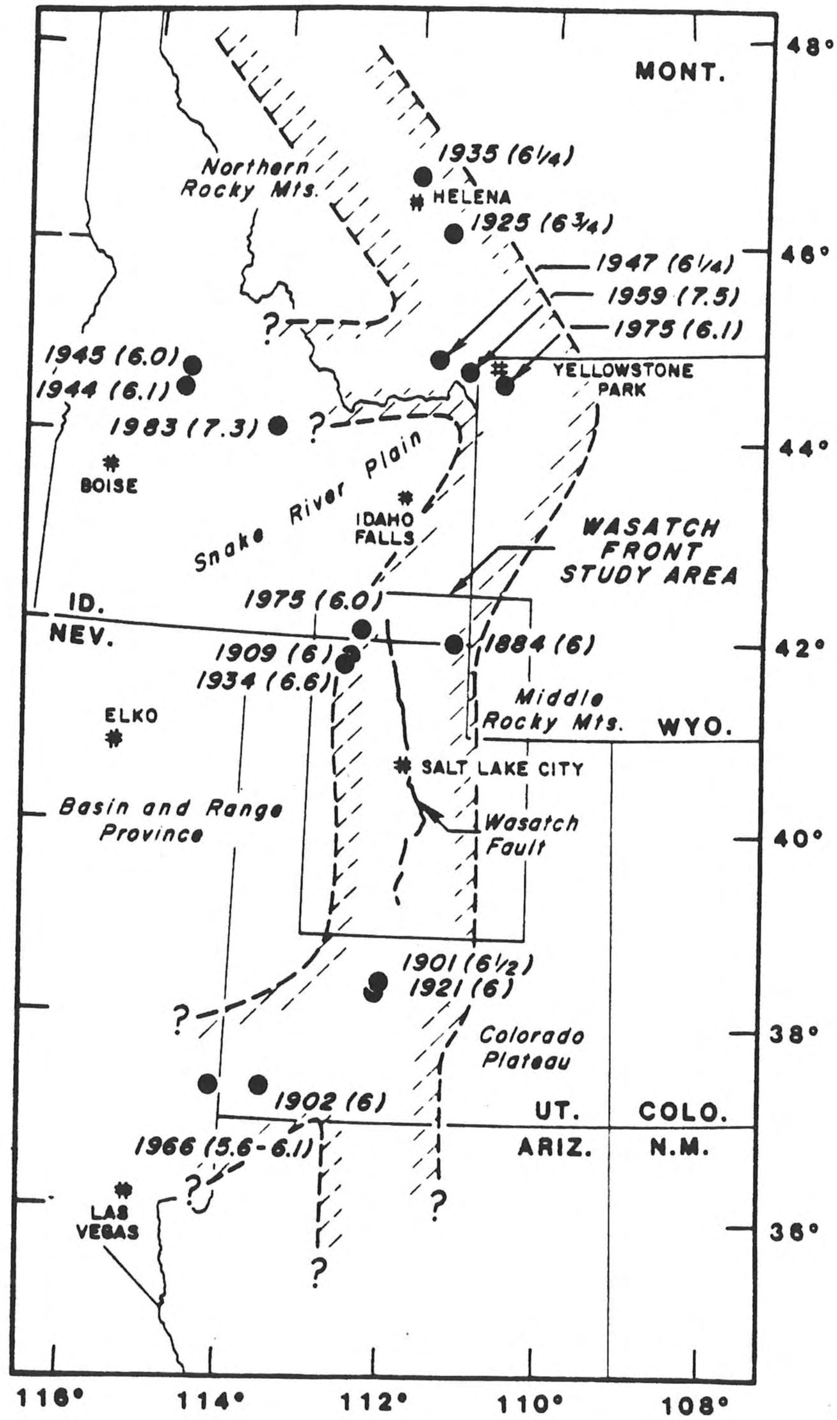


Figure 5.

Map showing setting of the Wasatch Front study area with respect to the Intermountain seismic belt (hachured zone) and the epicenters of historical earthquakes of magnitude 6.0 and greater (large dots). Year and magnitude labeled for each earthquake.

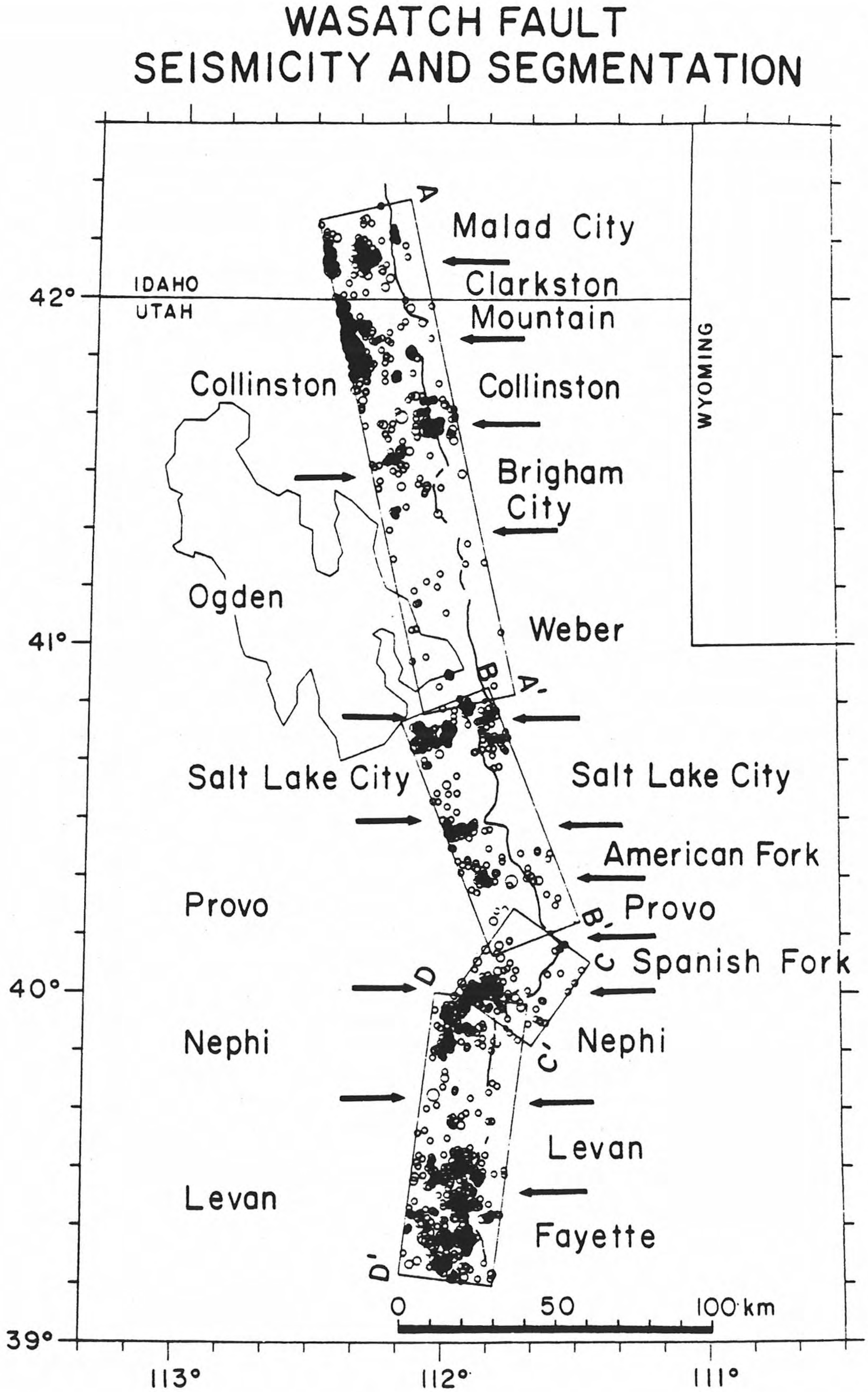
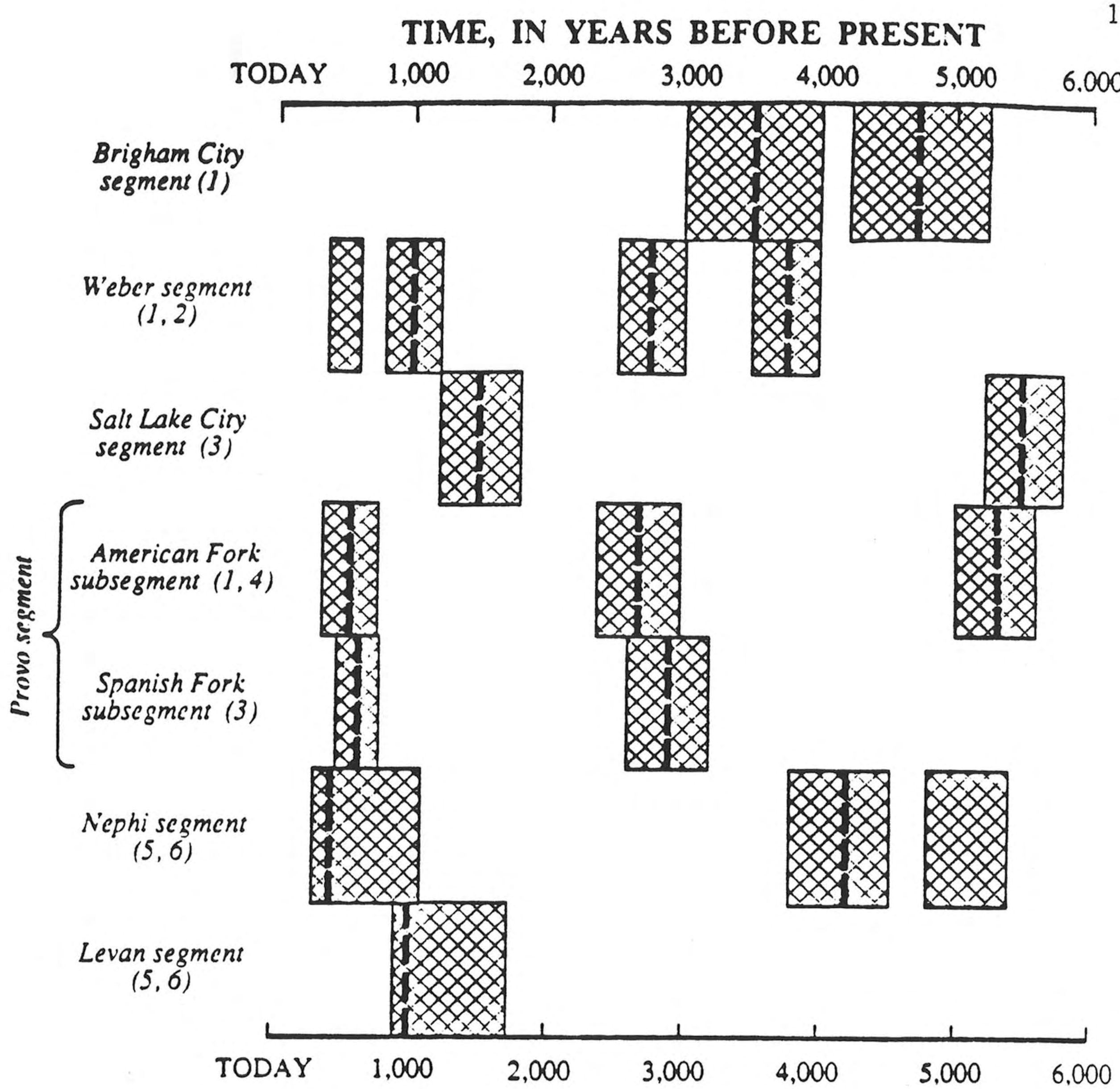


Figure 6.

Strip map showing the Wasatch fault, segment boundaries and names (according to Machette and others, 1989, right-hand side; and Schwartz and Coppersmith, 1984, left-hand side), and all earthquakes located by the University of Utah Seismograph Stations during the period July 1962 through December 1986. Circle sizes indicate relative magnitudes of events.



Sources of information:
(1) Machette and others (1987), modified in this report.
(2) Swan and others (1980), modified in this report.
(3) Schwartz and others (1988), modified in this report.
(4) Forman and others (1989).
(5) Schwartz and Coppersmith (1984).
(6) Jackson (1988).

Figure 7.

(taken from Machette and others, 1989)

central part of the fault zone—ranges from a maximum of 415 years to a minimum of 340 years. For these segments, the elapsed time since last rupture has been longest on the Brigham City and Salt Lake City segments (3,500 and 1,500 years, respectively) (Fig. 7). The most recent surface-faulting earthquake on the Wasatch fault occurred about 400 years ago on the Nephi segment.

- Historical main shocks of estimated Richter magnitude 4.0 or greater in the Utah region are shown in Figure 8. The historical sample includes at least 15 independent main shocks that have had an estimated Richter magnitude of 5.5 or greater.

- The largest historical earthquakes in the Utah region have been the magnitude (M_S) 6.6 Hansel Valley, Utah, earthquake of 1934 and an earthquake near Richfield, Utah, in 1901 that had about the same size (Fig. 8).

- Moderate, potentially damaging earthquakes without surface rupture (magnitude 5.5 to 6.5) occur on average once every 6 to 7 years somewhere in Utah. Because of their broad distribution (Fig. 8), such earthquakes are a fundamental source of seismic hazard throughout Utah's main seismic belt.

- The map pattern of 10,732 small to moderate-sized earthquakes (up to magnitude 6.0) located by the University of Utah since mid-1962 (Fig. 9) emphasizes the nearly statewide extent of seismic activity in Utah. Seismicity predominates, however, along a roughly 200-km-wide zone defining the Intermountain seismic belt.

Ground-Shaking Hazard

- In any 50-year time period, there is a 10 percent probability that the levels of peak horizontal ground acceleration and velocity at sites underlain by firm sediments will exceed 0.25 g and 18 cm/s, respectively, along the Wasatch Front.

- Based on recordings of distant nuclear explosions in Nevada, it is known that sediment properties in Salt Lake Valley can produce substantial geographical variation in the level of ground motions. Mean spectral estimates of low-amplitude ground-motion values are increased by factors of 6 to 10 or more in some sections of the valley, compared to hard rock, for the period range 0.2 to 3.0 seconds. The implication of such large site factors is that an earthquake of a given size at a given distance is likely to be more destructive in the Salt Lake area than in, say, the Los Angeles area.

- Because of the nature of geologic site conditions in Salt Lake Valley, the ground-shaking hazard to high-rise structures sited over deep and soft valley sediments (fine sand and lake-clay deposits) is likely to be enhanced compared to the hazard at sites

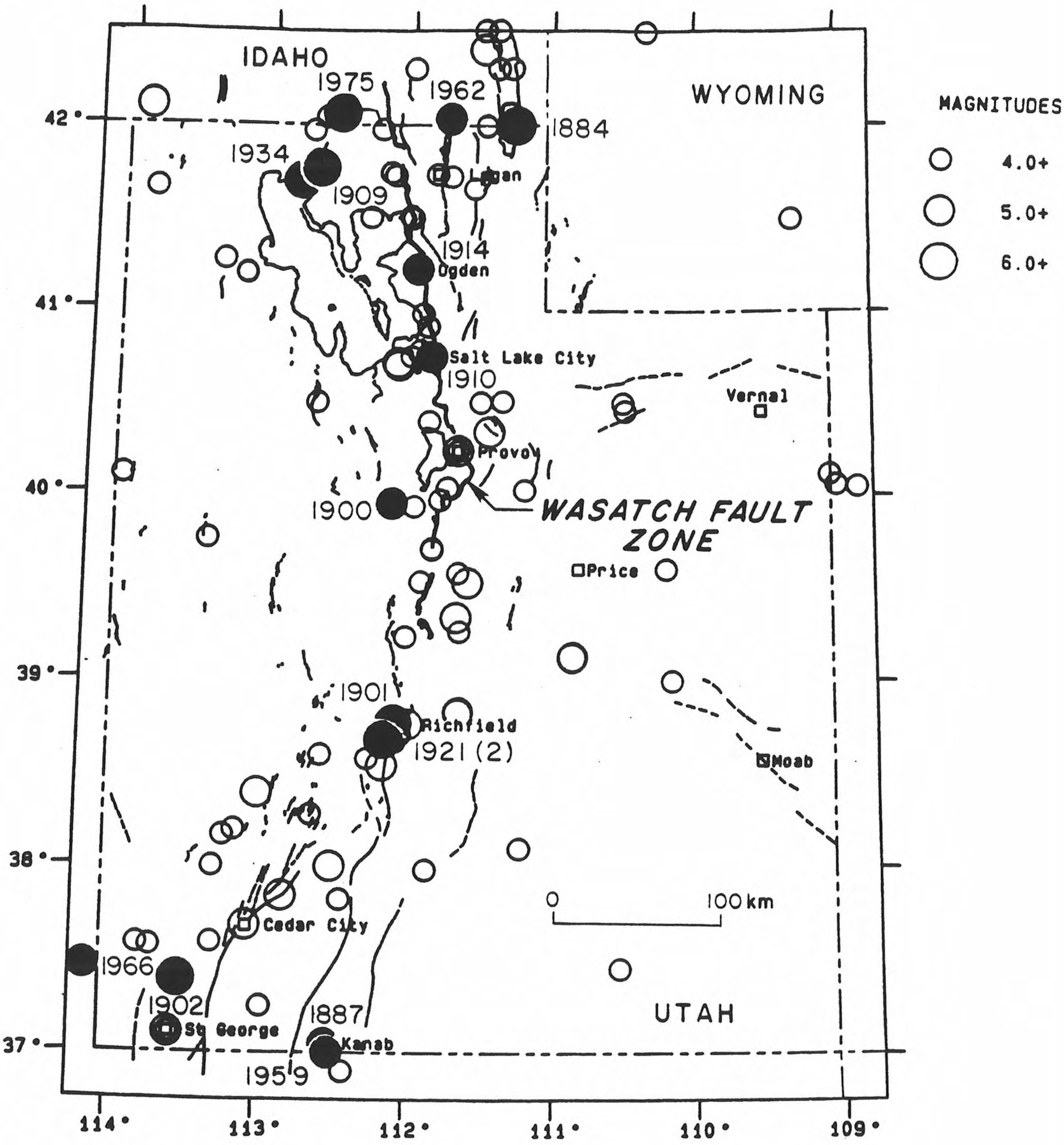


Figure 8.

Epicenter map of the Utah region showing all independent main shocks of M_L 4.0 or greater (or Intensity V or greater), 1850-June 1989, and Quaternary faults. Earthquakes of estimated M_L 5.5 or greater are indicated by solid circles labeled with date. Data from University of Utah Seismograph Stations.

SEISMICITY OF UTAH

(JULY 1962 - MARCH 1989)

10,732 Earthquakes

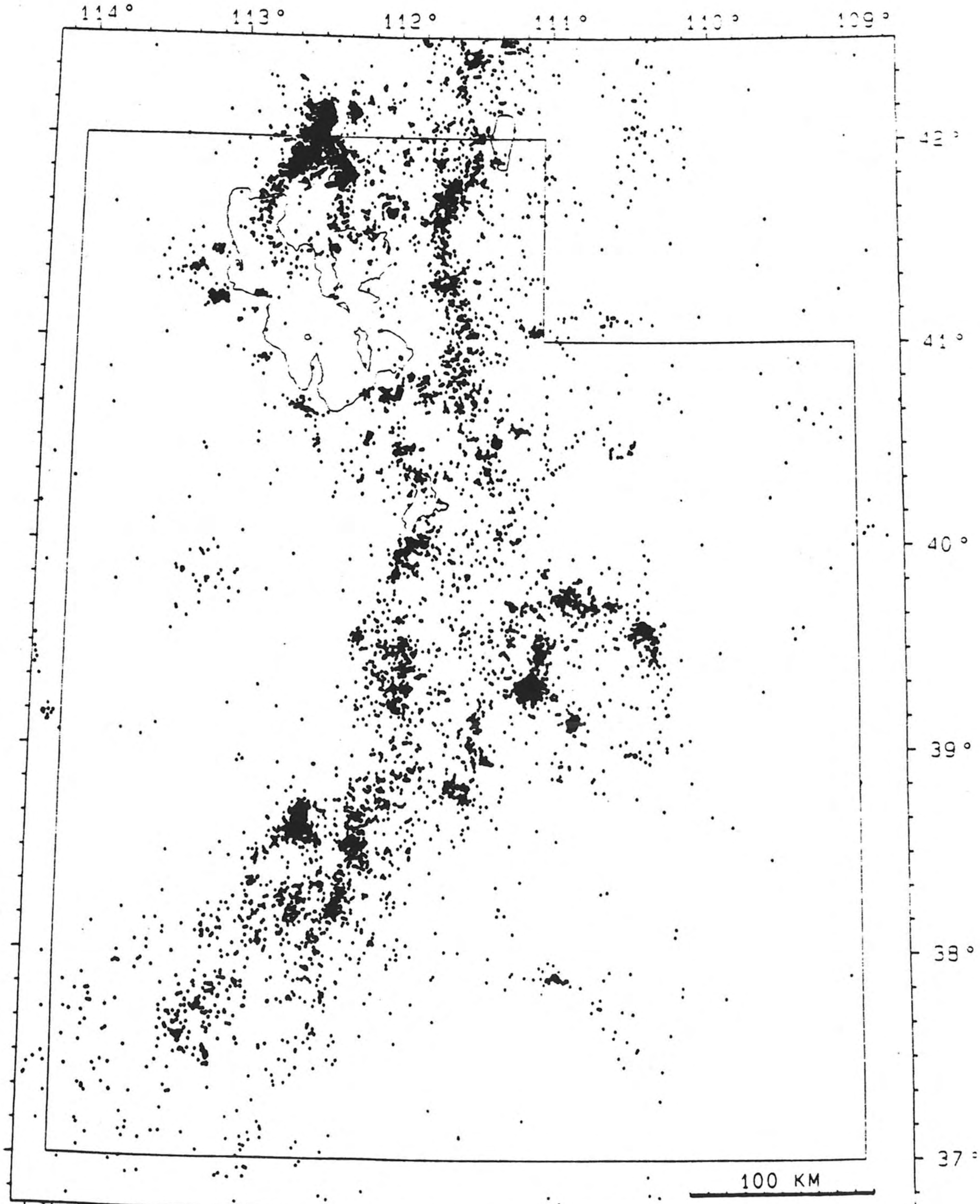


Figure 9.

underlain by coarse sand and gravel, especially for distant (50 to 250 km) earthquakes. For distant earthquakes, the ground motion levels that occur at the soft sediment sites are expected to be 6 to 10 times greater than at rock site, for periods greater than about 0.2 s.

- Some other serious problems accompanying large Wasatch Front earthquake will include: soil liquefaction, landslides, rock falls, and broad permanent tilting of valley floors—possibly causing the Great Salt Lake or Utah Lake to inundate part of Salt Lake City or Provo.

Loss Estimates

- In a magnitude 7.5 earthquake on a central part of the Wasatch fault, Utah should expect damage to buildings to exceed $4.5 billion in Davis, Salt Lake, Utah and Weber counties. This may represent only 20% of the total economic loss.
- Moderate-sized earthquakes producing a "direct hit" to one of the Wasatch Front's major cities could also produce major damage: more than $2.3 billion for a magnitude 6.5 earthquake—and more than $830 million for a magnitude 5.5 earthquake.
- Unreinforced masonry buildings (for example, brick homes built before 1960) are particularly vulnerable to ground shaking and are expected to account for 75% of the building losses. The Wasatch Front area has a sizable inventory of other structures not built with earthquake resistant design that will be seriously damaged.
- Surface-faulting, and other ground failures due to ground shaking during a large earthquake, will cause major disruption of lifelines (utilities, water, sewer), transportation systems (highways, bridges, airports, railways), and communication systems.
- As a result of the geographical concentration of state-owned buildings—and their limited seismic resistance —losses from a large Wasatch fault earthquake could easily reach 30 or 40 percent of replacement value. (Schools, hospitals, and fire stations were not studied.)
- A 1976 study by the U.S. Geological Survey for a worst-case earthquake on the central Wasatch fault estimated 2,300 fatalities (assuming no dam failures), 9,000 injured, and 30,000 homeless. The experience of the 1988 Armenian earthquake—and more up-to-date engineering judgment about the collapse potential of many structures in the Wasatch Front area—suggests the 1976 fatality estimate is low.

Utah's State Earthquake Program

As part of the National Earthquake Hazards Reduction Program (NEHRP), the U.S. Geological Survey in 1983 targeted Utah's Wasatch Front region for a five-year program of focused research, the refined assessment of earthquake hazards and risk, and the implementation of measures to reduce potential earthquake losses. The NEHRP five-year program effectively catalyzed the cooperative involvement of scientists, engineers, planners, emergency-management officials, and public and private leaders in addressing Utah's earthquake problems. As a result, Utah's earthquake program has solid underpinnings for action in terms of adequate technical information, trained and committed people, and public support (see Attachment No. 3). Steps towards hazard-reduction measures are constantly gaining momentum. For regions outside of California, Utah's state earthquake program is one of the best-positioned for becoming a national showcase for the NEHRP. (We argue, however, that future successes will depend on a continuing flow of complete, timely, and accurate earthquake-related information—increasingly relying on modern technology.)

At the state level, Utah's earthquake program is led by a coalition of the Utah Geological and Mineral Survey, the Utah Division of Comprehensive Emergency Management, and the University of Utah Seismograph Stations. State-federal partnership arises from the cooperative federal involvement of the U.S. Geological Survey, the Federal Emergency Management Agency, and the National Science Foundation. Earthquake-hazard-reduction activities to date in Utah have been predominantly funded by these federal agencies, and federal researchers and planners were heavily involved in the 1983-88 NEHRP Wasatch Front program.

Since the 1960's, the University of Utah Seismograph Stations (UUSS) has been the lead scientific organization in Utah for seismic monitoring and associated seismological research. As part of the University's Department of Geology and Geophysics, the UUSS is an integral part of the University's academic mainstream. It encompasses a group of three Ph.D. seismologists (1 regular faculty member, 2 research faculty members), 6 full-time staff, and 11 part-time staff and students. Activities of this scientific group involve an intimate mixture of university education, research, and public service.

UUSS seismologists have developed and operate a regional seismic network of (currently) 80 seismic recording stations (described in the paper for Element A). The network of 55 stations covering the Utah region, directly germane to this briefing paper, is cooperatively supported by the state of Utah, the U.S. Geological Survey, and (in very minor part) by the U.S. Bureau of Reclamation. The seismic network provides data for basic research on earthquake seismology in the Intermountain seismic belt, essential information for analysis of earthquake hazards and risk in Utah, information used for engineering applications, and timely information used for emergency management. UUSS currently has a total annual budget of about $670,000 for earthquake seismology; state funds make up $217,700 of this amount for 1989-90 (77% for network operations in Utah and 23% for associated research). Operational costs for the seismic-network operations in Utah (exclusive of research) are about $370,000 per year. (Attachment No. 6 and Appendix A-1 in Element A provide other relevant details about the UUSS.)

The Utah Geological and Mineral Survey (UGMS) is responsible for delineating Utah's geologic hazards, including earthquake hazards, and is the state's repository of information for all geological hazards. UGMS geologists advise state and local governments about geological hazards as part of site investigations of critical facilities. UGMS has an annual budget of $2.2 million, of which $400,000 is for hazards identification (including approximately $100,000 specifically for earthquake projects). Federal funding for the UGMS earthquake program averages about $75,000 per year.

Activities of the Utah Division of Comprehensive Emergency Management (CEM) include: (1) promoting earthquake awareness and education at all levels; (2) developing state and local plans for earthquake preparedness and formal response; (3) conducting earthquake exercises using scenarios provided by the UGMS and UUSS; (4) assessing risk and vulnerability of critical structures, facilities, and lifelines; (5) providing training for mitigation and response; and (6) coordinating procedures for warning and response with other state and local agencies. CEM also coordinates state agency participation in the plan for federal response to a catastrophic earthquake (presently being drafted by FEMA Region VIII, Denver). CEM has an average annual budget of approximately $2 million, of which $374,000 is from state funding. Several CEM programs are multihazard-oriented. CEM's earthquake program has an annual budget of $72,000 (50 percent federally funded).

Several other state agencies contribute to Utah's earthquake-hazard-reduction efforts, and all state agencies have response plans in the event of a damaging earthquake. Each of Utah's universities has contributed to developing an improved understanding of earthquake hazards within the state. Several state agencies—notably, the Division of Facilities Construction and Management, the Department of Transportation, and the Department of Water Rights—have specific responsibilities with respect to construction safety and earthquake risk.

The Challenge

Utah has a unique window of opportunity to accelerate seismic safety by capitalizing on groundwork laid by the 1983-88 Federal/State NEHRP program. At reasonable expense, Utah can develop an instrumentation program to deal with its earthquakes coherently and effectively. Given the enormous state resources at risk to earthquakes and the anomalous concentration of 80 to 90 percent of Utah's population along the state's most dangerous earthquake zone, can Utah afford *not* to invest in earthquake instrumentation? The following instrumentation proposals will try to demonstrate that modern technology and resulting information can indeed increase seismic safety.

Each of the instrumentation plans you're about to review begins with a statement of an important, longstanding problem. In drafting the respective plans, attempts were made, first, to motivate action at long last to get *something* done towards reaching a solution and, second, to promote future-think—to set challenging goals that will really make a difference in lessening the earthquake threat in Utah. We offer a few thoughts:

- Seismology is well recognized as an *observational* science—inherently dependent on instrumentation.
- Further, earthquake seismology (in Utah and elsewhere) is at a plateau where the limitations of out-of-date instrumentation are a continual source of handicap and frustration for both scientists and engineers.
- The plans implicitly involve partnerships: state-federal partnership, partnerships among state and local agencies, and—importantly—a fundamental partnership between seismological researchers at the University of Utah and state government whose needs they've continually tried to anticipate and meet.
- The plans reflect literally years of careful considerations about the problems at hand by Utahns and by various national committees and working groups.
- Thought has been given to what can be handled without an extraordinary increase in base-budget support. None of the instrumentation requests are "pie in the sky" or "wish lists."
- Personnel requirements and recurring costs can't be ignored, and attempts have been made to identify those costs in each plan.
- Inexpensive equipment options can result in larger labor costs and expenditures of time—by electronics engineers, computer specialists, and field technicians—to make various inexpensive equipment configurations work reliably.

- Surveys of community leaders and the general public along the Wasatch Front show strong support for actions to reduce earthquake risks—and most of the people surveyed identify local and state government as having a major responsibility to take action (see Attachment No. 7).

ELEMENT A

Modernizing Seismic-Network Instrumentation

by W.J. Arabasz, J.C. Pechmann, E. McPherson, S.J. Nava, and R.B. Smith

The status quo is not an option . . . . Any regional seismic network that fails to modernize is doomed to mediocrity and even irrelevance.

Panel on Regional Seismic Networks, National Research Council (Meeting Notes, 1989)

THE AUTHORS

All are affiliated with the University of Utah Seismograph Stations.

Foreword

> *Regional seismic networks are fundamentally wide-area communication networks requiring complex electronics, all-weather remote field installations, telemetry systems for continuous data transmission, elaborate central-recording laboratories with dedicated computers and peripherals for recording and data processing, and well trained scientists, technicians, and data analysts for efficient and productive operations.*
>
> *Panel on Regional Seismic Networks, National Research Council (in press)*

Because seismic networks are coherent systems with many parts, this plan for modernizing seismic-network instrumentation in Utah necessarily has many parts too. To make our plan understandable, we need first to present some background information.

The University of Utah regional seismic network involves the operation and centralized recording of 80 seismograph stations. (Basic details of the seismic network and associated costs are described in Appendix A-1.) The University of Utah network is one of about 50 seismic networks in the United States—and one of eight U.S. networks operating more than 50 stations.

In 1983, the Committee on Seismology of the National Research Council identified unstable funding and obsolete equipment as a national problem seriously jeopardizing regional seismic networks—including the one operated by the University of Utah. Subsequently, reports by a national Ad Hoc Committee on Regional Networks, the U.S. Geological Survey, and the National Research Council's Panel on Regional Seismic Networks (report in review stage) have all reinforced the urgency to stabilize and modernize what are patently a fundamental resource for basic science and earthquake hazard mitigation. One of us (WJA) has been involved in the writing of the latter three committee reports, each of which has aimed (1) to make a convincing case for the intrinsic value of regional seismograph networks, (2) to describe the seriousness of persistent problems in the current configuration and operation of these networks, and (3) to outline recommendations for their modernization and future evolution.

A key document accompanying this briefing paper as Attachment No. 8 is a "National Seismic System Science Plan," an accurate reflection of the consensus view of the U.S. seismological community regarding the value, present shortcomings, and desired future of regional seismic networks. In particular, we point the reader to the sections entitled: "Uses of Current Regional Networks" (p.3), "Limitations of Existing Networks" (p. 15), "The U.S. National Seismic Network" (p. 17), "Relationship Between Regional and National Seismic Networks" (p. 21), and "Need to Develop Digital Regional Networks."

At the outset, there are five important points we we want to emphasize:

- The University of Utah's network is NOT operated simply to record and locate earthquakes. Figure A-1 outlines the many functions of a regional seismic network, and every function described therein applies to Utah's network.

- Network seismologists are NOT simply "historians" or "post-mortem analysts." Seismological data acquired from regional networks and from arrays of portable seismographs are used *predictively* (1) to identify and characterize the potential source regions of future earthquakes of concern, (2) to quantify the expected level and nature of future damaging ground shaking at any site for engineering and risk applications, (3) to recognize, in a probabilistic way, seismicity changes that may precede a moderate or large earthquake, and (4) to assess time-varying probabilities for damaging aftershocks and/or a larger main shock once a sizable earthquake occurs.

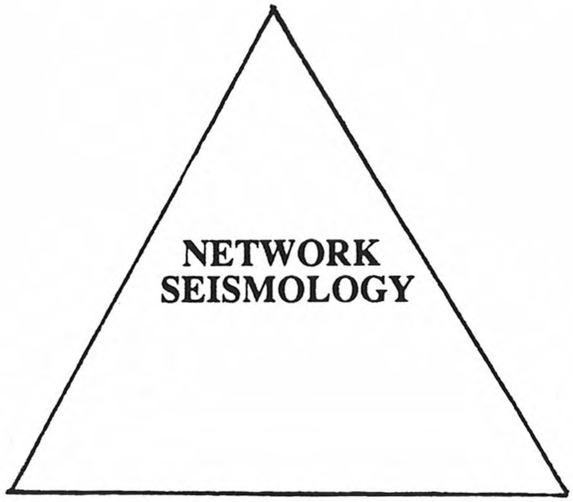
- The future development of a U.S. National Seismic Network (USNSN) with high-quality, widely-spaced stations and satellite telemetry (Fig. A-2) will NOT obviate the need for a modern regional seismic network in Utah. Figure A-3 graphically illustrates that "the National Seismic Network (will be) far too sparse to study detailed features of regional seismic activity." The concept of a National Seismic *System* (Attachment No. 8) envisions the linking of modernized regional seismic networks (covering the nation's major seismic zones) with widely-spaced USNSN stations. This will be done by interfacing regional network recording centers with the USNSN master station in Golden, Colorado, through satellite communications (Fig. A-2, below).

- The arrival times, amplitudes, and frequencies of seismic waves all carry critical information about the earthquake source, propagation path, and conditions beneath the recording site. And this information can only be captured effectively using digital technology and state-of-the-art seismic sensors. In a nutshell, existing analog seismic instrumentation serves well to capture the arrival times of earthquake waves for earthquake locations, but it fails to capture important amplitude information onscale (because of dynamic-range problems) and important frequency information (because of bandwidth limitations).

- Crustal earthquakes that occur throughout the western United States generally originate at depths shallower than 15 to 20 km. The map location (epicenter) of such earthquake sources can be resolved accurately if the epicenter is adequately surrounded by recording stations, but their depth can only be resolved reliably if there is a recording station within one focal depth of the epicenter. The latter requirement motivates the density of seismograph stations in California (Fig. A-4). By comparison, the station density in Utah, constrained by economics, is relatively sparse. Less than 10 percent of the earthquake locations in Utah have reliable focal depths.

REGIONAL SEISMIC NETWORKS

Function: Scientific Research
Users: (Scientists and Engineers)



Earthquake Monitoring & Rapid Emergency Response
(Public Safety Officials, News Media & General Public)

Uses of Current Regional Networks

Regional seismic networks are a fundamental multipurpose tool of observational seismology. Although commonly perceived as simply a tool for earthquake "surveillance" or "monitoring," existing seismic networks provide data and information for a host of uses:

- –Public safety and emergency management
- –Quantification of hazards and risk associated with both natural and human-triggered earthquakes
- –Surveillance of underground nuclear explosion
- –Investigation of earthquake mechanics and dynamics
- –Investigation of seismic wave propagation
- –Investigation of seismotectonic processes
- –Earthquake forecasting and prediction research
- –Probing the internal structure of the Earth

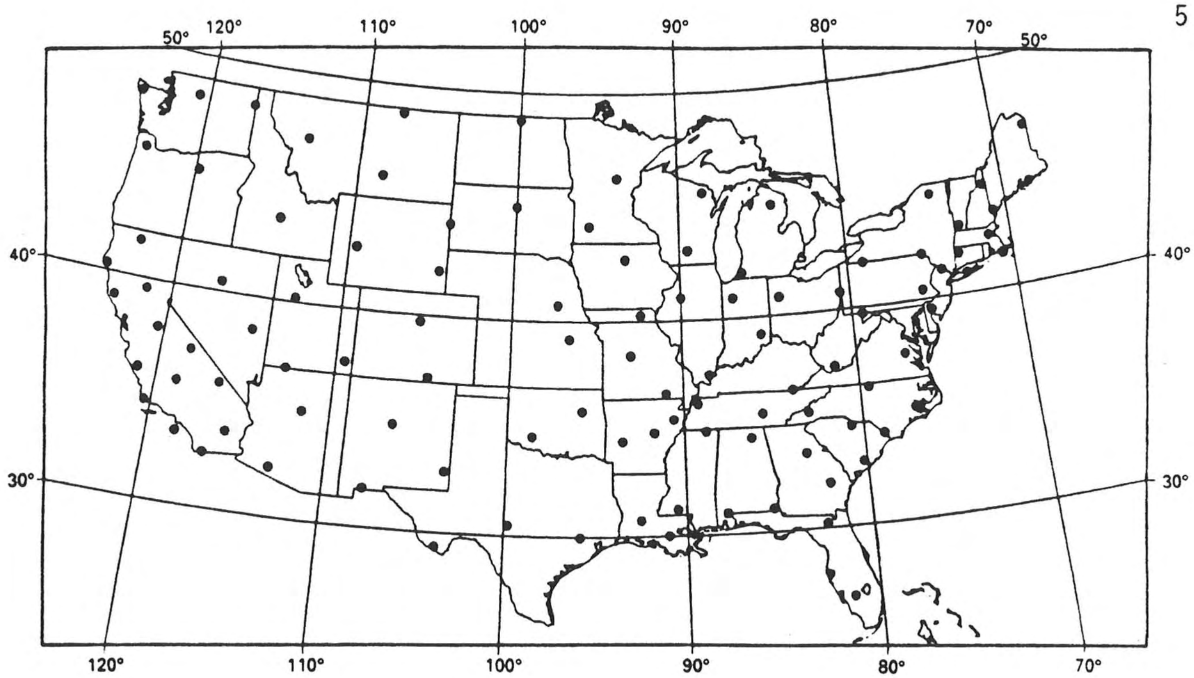
Importantly, seismic networks are also key facilities for the graduate education and training of this country's professional seismologists, and they provide direct outlets for public information and for expert assistance to public policy makers, planners, designers, and safety officials.

Input to Earthquake Hazard & Risk Analyses, Earthquake Engineering
(Engineers, Public Officials & Other Decision Makers)

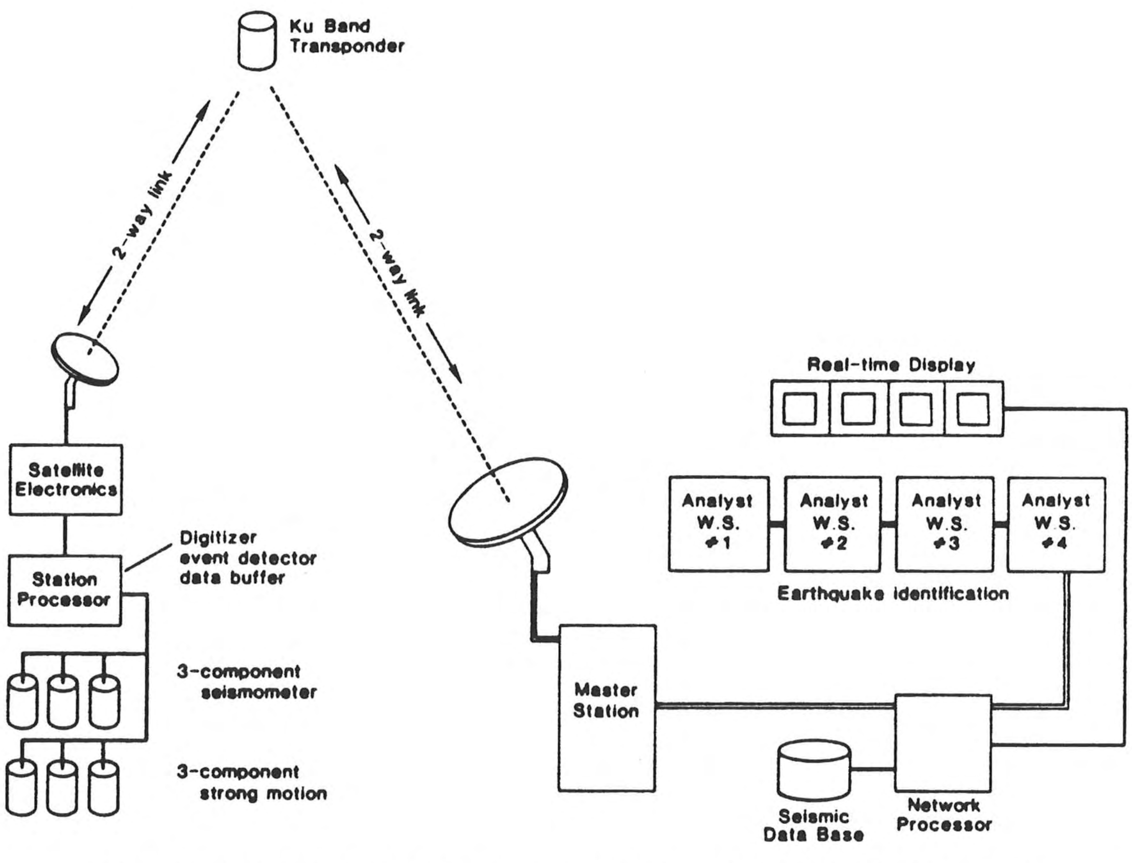
- Earthquake data base
- Seismotectonic framework
- Earthquake source identification
- Seismicity parameters & earthquake occurrence modeling
- Information for predicting strong ground motion (source mechanics, attenuation)

Figure A-1.

The many practical and important functions of regional seismic networks. (Inset taken from Attachment 8, p. 3).



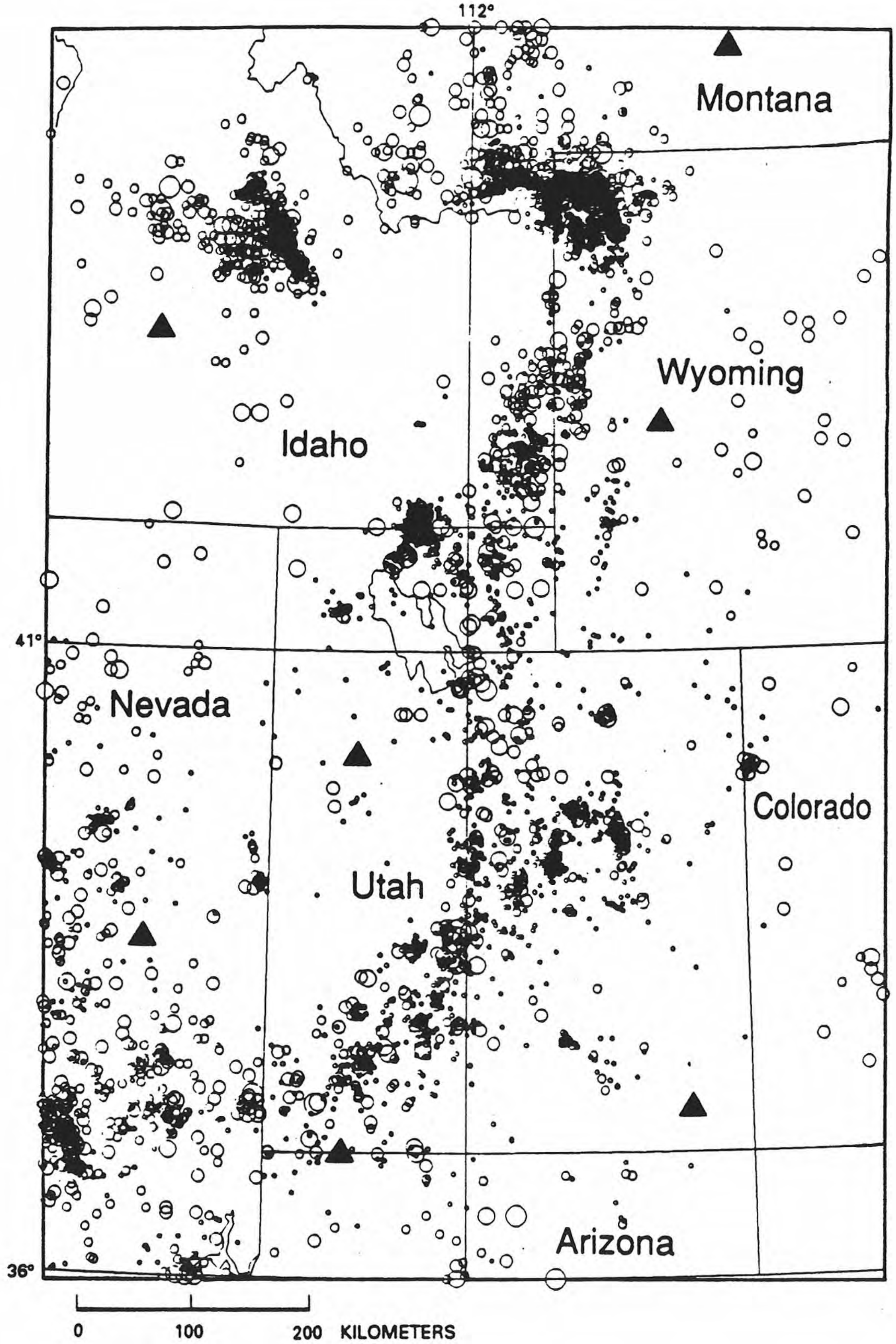
Proposed National Seismic Network stations in the contiguous United States. Additional stations are proposed for Alaska, Hawaii, and Puerto Rico. Only stations east of the Rocky Mountains in the contiguous United States are currently funded (from Massé and Buland, 1987).



Schematic representation of National Seismic Network. Three-component, force-balance, broad-band seismometers (both high and low sensitivity) are digitally recorded at the station for a total dynamic range of approximately 10 decades (200 dB). Significant seismic signals detected at the station processor are telemetered via satellite to the Master Station in Golden, Colorado, for analysis and archival.

Figure A-2.

Map of proposed station sites (above) and schematic of satellite telemetry scheme for a National Seismic Network (taken from Attachment 8, p. 21-22).



Seismicity of the intermountain region located using the 75-station regional network operated by the University of Utah. Earthquakes since 1962 and larger than magnitude 2.0 are plotted. Proposed station locations for the National Seismic Network (triangles) illustrate that the National Seismic Network is far too sparse to study detailed features of regional seismic activity (courtesy of R. Smith, R. Engdahl, and J. Dewey).

Figure A-3.

Seismicity of the Utah region and proposed stations (triangles) of the National Seismic Network (taken from Attachment 8, p. 23).

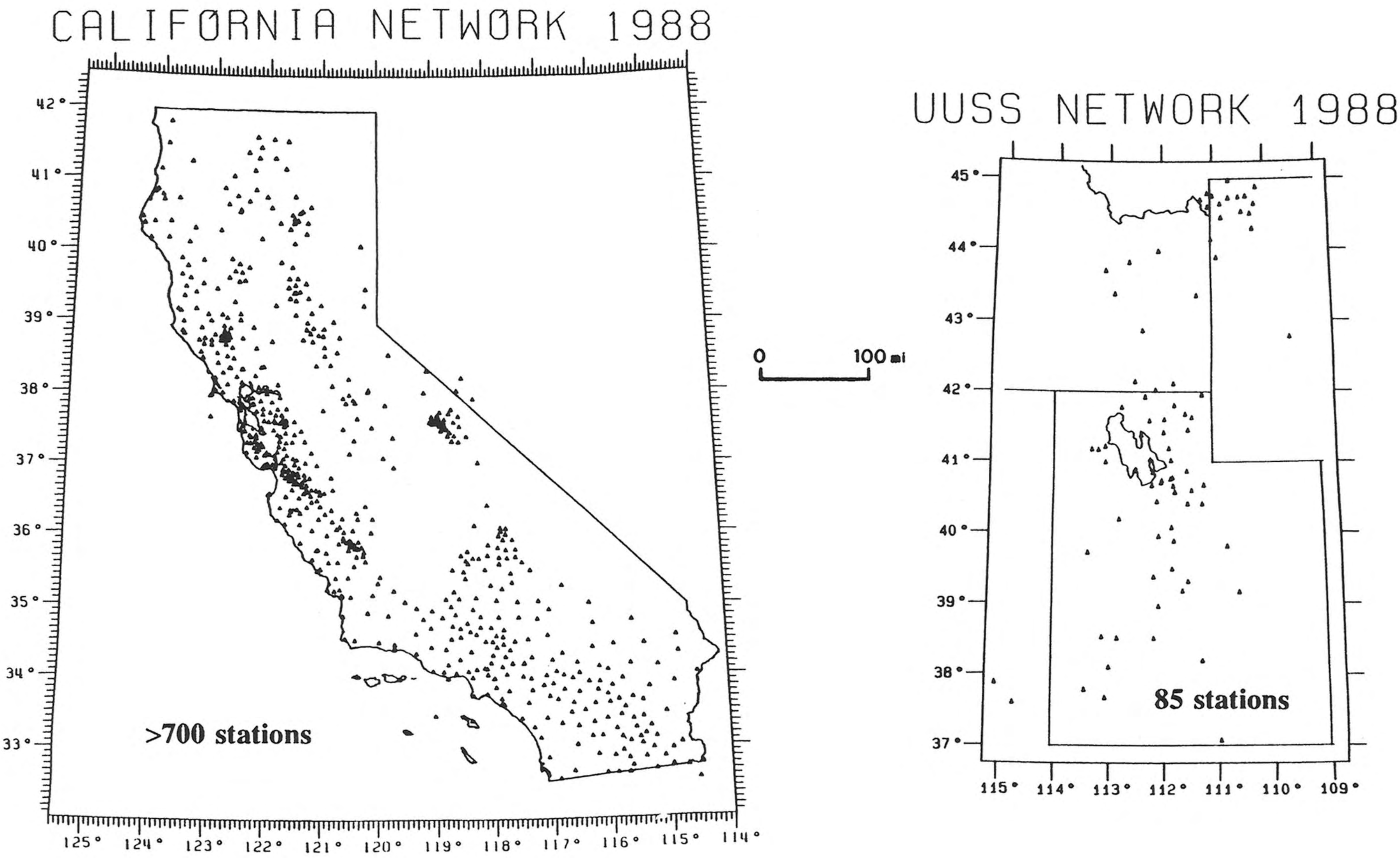


Figure A-4.

Comparison at same scale of the density of seismograph stations in California and in the Utah region.

Statement of General Problem

Existing seismic-network facilities in Utah for the recording and study of earthquakes are technologically outdated, unreliable because of aging, and fundamentally inadequate to the meet important needs for public safety, basic research, and engineering applications.

General Goals

- Achieve (1) reliably continuous and redundant recording of seismic data and (2) effective temporal surveillance of earthquakes of magnitude 2.0 and greater in the Utah region.
- Establish a robust, cost-effective, and versatile infrastructure for digital data transmission and centralized processing/recording that will allow network expansion and evolutionary upgrading to a modern digital seismic network.
- Overcome existing analog network's limitations of low dynamic range, narrow bandwidth, and single-component sensing so that the ground motions of significant moderate to large earthquakes in Utah can be "captured" with high fidelity for important practical and scientific reasons.
- Improve hypocentral resolution and magnitude sensitivity for (1) ongoing monitoring of as many important seismic source zones as feasible, with top priority on segments of the Wasatch fault along the Wasatch Front urban corridor, and (2) temporary monitoring where significant earthquakes occur in inadequately instrumented areas.
- If interest and support is forthcoming from the state, expand seismic-network coverage in Utah, aiming for more uniform coverage in seismically active parts of the state that are either presently uninstrumented or have inadequate coverage.

General Plan—A Road Map

The next step in making our multi-part instrumentation plan for network modernization understandable is to give you a road map. Our plan will have the following parts:

I. Replacement of Seismograph Stations Computers

II. Expanded Access to the State Microwave System

III. Upgrading and Expansion of Selected Network Stations

(A) Upgrading of 10 Existing Stations to Broadband Digital Stations
(B) Establishing 10 New Single-Component Digital Stations Along the Wasatch Fault
(C) Establishing 7 New 3-Component Regional Stations in Utah (Initially Analog and Later Upgraded to Digital)

IV. Interface with U.S. National Seismic Network

We'll use the flowchart in Figure A-5 together with a map of Utah's existing state microwave system (Fig. A-6) and a map of existing and proposed network stations of various configurations (Fig. A-7) to describe our proposed plan.

Steps 1, 3, and 4 of the flowchart deal with the need to establish a solid infrastructure for evolution of our network, in part to achieve modern broadband digital seismometry and digital telemetry. Replacement of our 1970's-era PDP-11/34 and 11/70 computer (Step 1) is absolutely essential. Solidifying our use of Utah's state microwave system (Steps 3 and 4), we feel is a cost-effective and sound strategy. Steps 2, 5, 6, 7, and 8 relate to upgrading and expanding selected parts of our network. Finally, Step 9 completes the eventual integration of our upgraded network with the U. S. National Seismic System. We proceed stepwise to elaborate on each part of the general plan—presenting either elaborate or generalized discussions as the case warrants. For convenient tracking, the approximate one-time cost for each step is indicated on the flowchart.

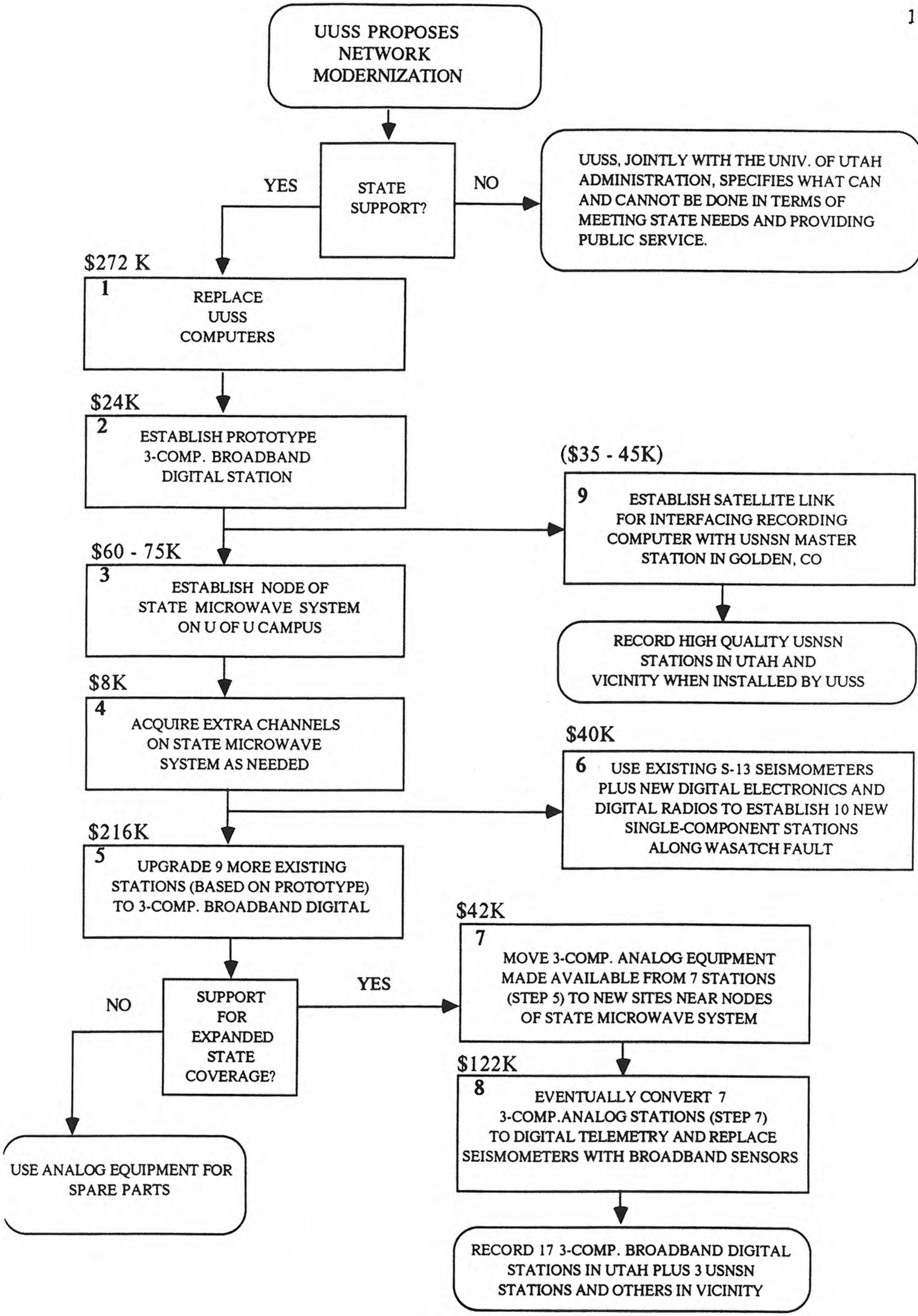

UUSS PROPOSES NETWORK MODERNIZATION
STATE SUPPORT?
YES
NO
UUSS, JOINTLY WITH THE UNIV. OF UTAH ADMINISTRATION, SPECIFIES WHAT CAN AND CANNOT BE DONE IN TERMS OF MEETING STATE NEEDS AND PROVIDING PUBLIC SERVICE.
$272 K
1 REPLACE UUSS COMPUTERS
$24K
2 ESTABLISH PROTOTYPE 3-COMP. BROADBAND DIGITAL STATION
($35 - 45K)
9 ESTABLISH SATELLITE LINK FOR INTERFACING RECORDING COMPUTER WITH USNSN MASTER STATION IN GOLDEN, CO
RECORD HIGH QUALITY USNSN STATIONS IN UTAH AND VICINITY WHEN INSTALLED BY UUSS
$60 - 75K
3 ESTABLISH NODE OF STATE MICROWAVE SYSTEM ON U OF U CAMPUS
$8K
4 ACQUIRE EXTRA CHANNELS ON STATE MICROWAVE SYSTEM AS NEEDED
$40K
6 USE EXISTING S-13 SEISMOMETERS PLUS NEW DIGITAL ELECTRONICS AND DIGITAL RADIOS TO ESTABLISH 10 NEW SINGLE-COMPONENT STATIONS ALONG WASATCH FAULT
$216K
5 UPGRADE 9 MORE EXISTING STATIONS (BASED ON PROTOTYPE) TO 3-COMP. BROADBAND DIGITAL
SUPPORT FOR EXPANDED STATE COVERAGE?
NO
YES
$42K
7 MOVE 3-COMP. ANALOG EQUIPMENT MADE AVAILABLE FROM 7 STATIONS (STEP 5) TO NEW SITES NEAR NODES OF STATE MICROWAVE SYSTEM
$122K
8 EVENTUALLY CONVERT 7 3-COMP.ANALOG STATIONS (STEP 7) TO DIGITAL TELEMETRY AND REPLACE SEISMOMETERS WITH BROADBAND SENSORS
USE ANALOG EQUIPMENT FOR SPARE PARTS
RECORD 17 3-COMP. BROADBAND DIGITAL STATIONS IN UTAH PLUS 3 USNSN STATIONS AND OTHERS IN VICINITY

Figure A-5.

State of Utah Microwave System Operated By Department of Public Safety

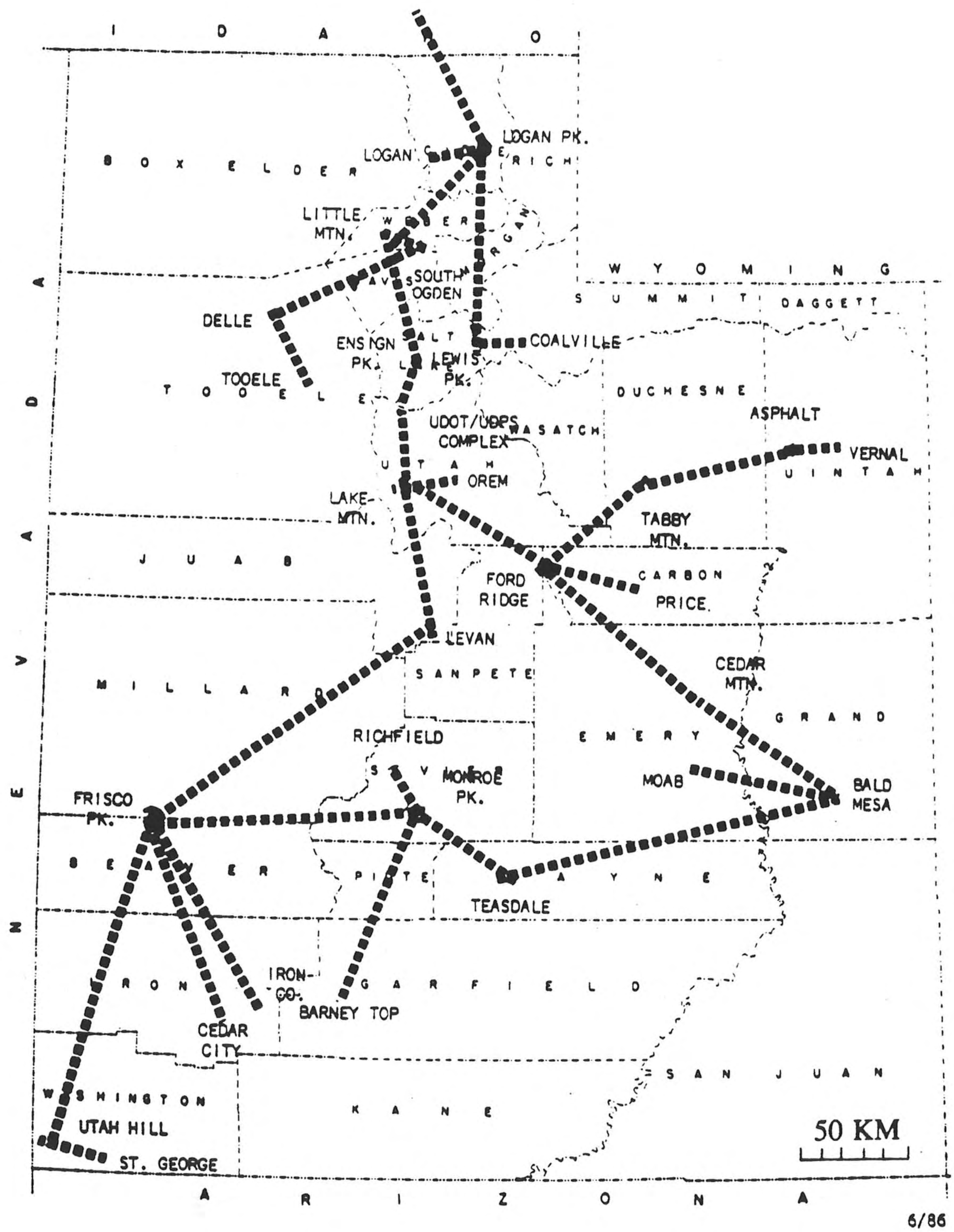


Figure A-6.

UTAH SEISMOGRAPH NETWORK

(SCHEMATIC FOR IMPROVED EARTHQUAKE RECORDING)

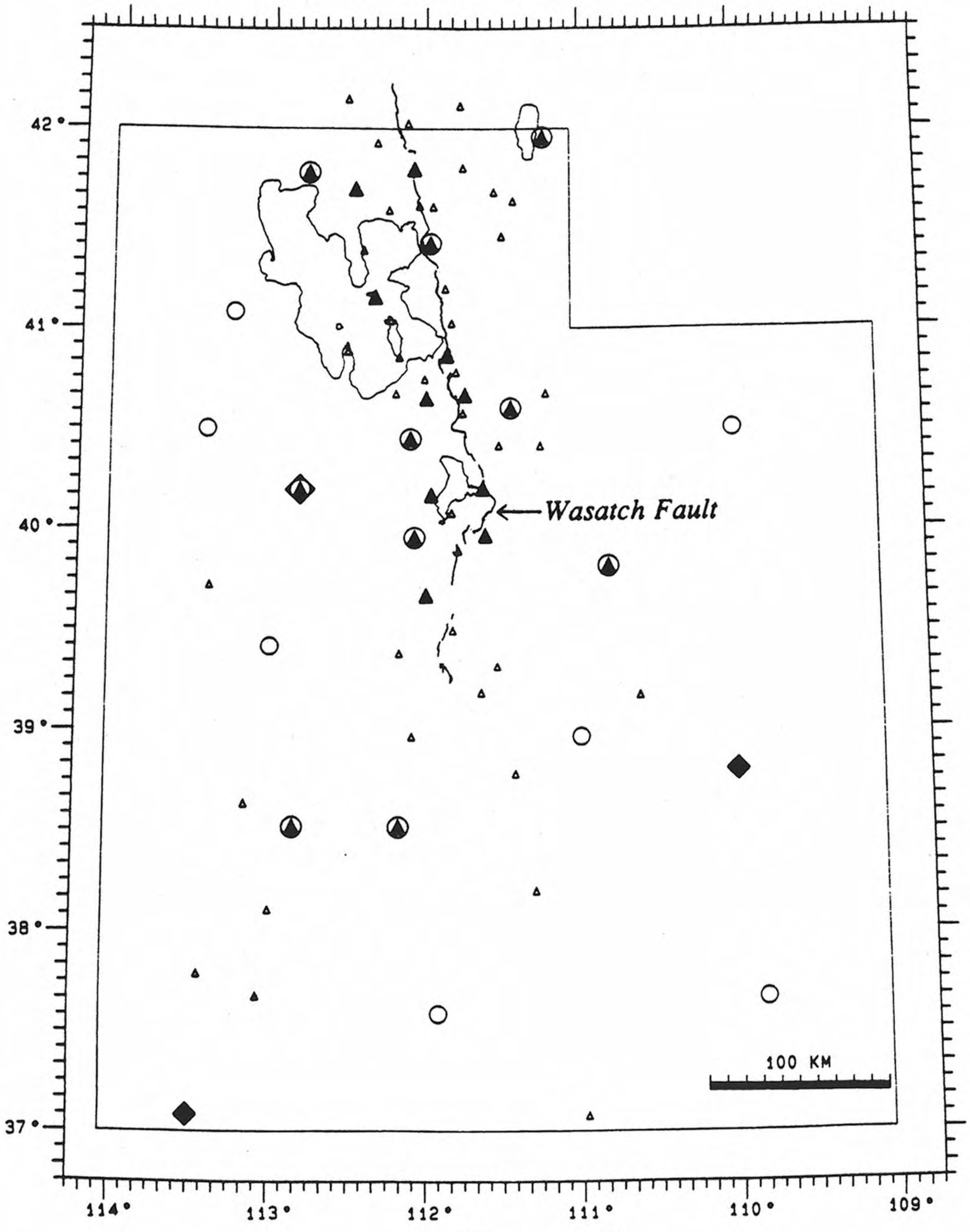


Figure A-7.

Map showing proposed upgrade of the Utah seismograph network. Open triangles show existing analog stations, open circles show proposed new three-component analog stations, solid triangles show proposed new vertical-component digital stations, solid triangles with circles around them show proposed upgrades of analog stations to three-component broadband digital stations, and solid diamonds show sites proposed by the U.S. Geological Survey for U.S. national network stations.

Part I. Replacement of Seismograph Stations Computers

Statement of Problem

Recording and analysis of data from the Utah seismic network currently takes place on two computers: (1) a Digital Equipment Corporation PDP-11/34 computer, dedicated to on-line detection and digital recording of seismic events, and (2) a companion PDP-11/70 computer for interactive data processing and analysis as well as research. These are mid-1970's vintage computers which have been in service since 1980, and are now woefully obsolete. Specifically, these computers have the following inherent limitations which require replacement of these machines before the seismic network can be upgraded to a state-of-the-art facility for earthquake recording and research:

- The PDP-11/34 stores the seismic data that it records on magnetic tape. No analysis of these data can take place until someone removes the tape from the PDP-11/34 and transfers it to the PDP-11/70. The time required to write the data onto tape and then read it onto another machine causes appreciable delays in the location of significant local earthquakes, particularly when no one is in the lab to transfer the tape immediately. Major hardware and software modifications would be needed to develop the capability for direct transfer of data from the PDP-11/34 to the PDP-11/70 or to any other computer.
- Tape write errors during earthquake recording on the PDP-11/34 frequently cause gaps in the recorded data that are three to ten seconds long. These gaps cause serious problems with the data analysis.
- The PDP-11/34 can only record data that arrive at the machine in analog form. The quality of the recorded data could be tremendously improved if the data were digitized at the seismometer sites and then transmitted and recorded in digital form.
- The PDP-11/34 is not able to identify large local earthquakes and generate an alarm when they occur. (The UUSS operates a real time picker (RTP) supplied by the U.S. Geological Survey which monitors incoming data from 64 of the 80 stations in the network and provides near real time determination of earthquake locations and magnitude. However, this system is not very reliable, and is not currently interfaced to any warning system.)
- The PDP-11/34 can only record data from 128 channels, 110 of which are now being used.
- The design of the PDP-11/34 and PDP-11/70 computers limits the data space for programs to a mere 64 kilobytes. This 64 kilobyte limit severely restricts their usefulness and prevents us from utilizing much of the new and improved software for

earthquake detection, location, and research. Most personal computers can run bigger programs than we can run on our PDP-11's.

- The age of both computers makes it increasingly difficult to buy and interface new peripheral devices for them. In most cases, the software to run these peripherals is either unavailable or requires extensive modification to work on the PDP-11's because of their memory limitations. The amount of staff time required to write or modify this type of software is excessive, unnecessary, and definitely not cost effective.
- Since 1980, the network data have been archived onto standard half inch magnetic tapes (at 1600 bpi), which cannot be relied upon for permanent data storage. Laser disks are now available which can be used to safely store data for much longer periods than it can be stored on magnetic tapes, and in far less space. However, it would be difficult if not impossible to find a laser disk with accompanying software for the PDP-11/70.
- In order to change the station list file or the triggering parameters on the PDP-11/34, it is necessary to shut down the data acquistion programs. Whenever we do this, we run the risk of losing valuable data.
- Both the PDP-11/34 and the PDP-11/70 are much more subject to hardware failures than modern minicomputers are. Furthermore, the PDP-11/34 is incapable of restarting itself after power failures like most modern data acquisition computers can.

Specific Goals

Our goal is to replace the PDP-11/34 and PDP-11/70 computers with new computers that do not suffer from the unnecessary and frustrating limitations described above. Replacement of these computers is a prerequisite for the modernization of the Utah seismic network and for the development of a modern communications system for transferring earthquake information. The greatly enhanced capabilities of these computers will allow the following:

- Recording of data directly on disk, which will make possible the automatic determination of earthquake locations and magnitudes in near real time using all of the available network data.
- Recording of high quality, broadband, wide dynamic range data telemetered in digital form from a selected subset of the UUSS network stations.
- Notification of UUSS personnel when a significant earthquake occurs in Utah.

- More rapid public notification of earthquake activity, especially outside of normal working hours.
- Expansion of the Utah network into areas of the state that are not currently covered, densification of the network along the Wasatch fault to enable more accurate determination of earthquake depths, and complete recording of ground motion (horizontal and vertical) at a larger number of stations.
- More effective research on earthquakes in Utah, which will lead to an improved understanding of earthquake hazards in the state.
- More productive use of staff time.
- Archiving of the valuable data acquired by the Utah network onto a more permanent storage medium.

Instrumentation Plan for Replacing UUSS Computers

We propose to replace the PDP-11/34 and the PDP-11/70 with two new computers which would be networked together; one for network recording and routine data processing and the other for data analysis and research. The desired specifications for these two new computers are given in the Appendix A-2 and A-3 to this paper. Two separate small computers are requested instead of just one large multipurpose computer in order to prevent data analysis and research activity from possibly interfering with the real time collection and processing of data.

Computer systems that meet our requirements for the data analysis and research computer are sold by many different vendors. On the other hand, the available choices for the network recording computer are very limited because of the specialized hardware and complex software needed to perform real time data acquisition from a modern seismic network and automatic background processing of these data. Our first choice at this time for the network recording system is an upgraded version of the HAWK system developed jointly by NEWT, Inc., and the University of Washington, which runs on a Masscomp 5600 minicomputer. The HAWK system is our first choice for the following reasons:

- The software for the HAWK system is available to us free of charge as an educational institution and is well documented. The availability of the software is a critical constraint, because the UUSS does not have the manpower to develop or even substantially modify such a large software package on its own.
- The HAWK system runs under the UNIX operating system, which is the operating system used by our PDP-11/70 and nearly all of the other computers within the Department of Geology and Geophysics and the College of Mines and Earth Sciences. We have a strong preference for a UNIX-based system because everyone on

the UUSS staff is already familiar with UNIX, it will be easier to transfer existing programs from the PDP-11/70 to another UNIX machine, and compatiblity with other computers within the College will greatly facilitate the transfer of data and programs between this machine and others. The data analysis and research computer will definitely have a UNIX operating system in order to maximize compatibility with other computers in the College and to facilitate implementation of new seismological software, most of which is now being developed on UNIX computers. If both the recording and research computers have the same operating system, it will greatly simplify the use of these computers by the staff and allow a straightforward network link between the two machines.

- The HAWK system has been successfully recording and processing data from the 110-station University of Washington regional seismic network since May 1988, and has proven its reliability and effectiveness. Furthermore, the HAWK system is the only UNIX-based system with a demonstrated capability to record data from a regional seismic network comparable in size to the Utah network. There are several computer systems available for recording data from small seismic networks, but these cannot be expanded to accomodate the number of stations in the Utah network.
- The HAWK system is upwardly compatible with our current data formats and with our current software for interactive data analysis, most of which was originally developed at the University of Washington. This compatibility will greatly minimize the amount of time required to complete the transition to the new system.
- The HAWK system can be modified to record data that is transmitted to the central recording facility in digital as well as analog form. This is the only significant modification that the HAWK system will need in order to meet our requirements. We know of only one seismic network recording system in the world that records both analog and digital data, a commercial system developed by NEWT, Inc. NEWT developed the original version of the HAWK system, and could add the capability to record digital data both from our own network and from the national network.

Justification for Computer Instrumentation Plan

- The computer systems now operated by the UUSS are embarrassingly obsolete unreliable, and inadequate for modern earthquake recording and research.
- The present recording computer is the major obstacle preventing conversion of a subset of the Utah seismic network to digital telemetry, a step which would enormously improve the quality of the recorded data.

- The existing recording computer requires frequent tape changing and manual rebooting after crashes. This need for constant attention leaves the system vulnerable to loss of data, especially outside of normal working hours.
- The existing computers cannot provide any warning to seismologists and emergency response personnel when a significant earthquake occurs in Utah.
- It takes an unnecessarily long period of time to locate earthquakes of immediate interest after they occur (usually 20-40 minutes, depending on the size of the earthquake and its position on the tape).
- Significant expansion of the Utah seismic network cannot take place unless the recording computer is replaced by one with greater channel capacity.
- Recording and analysis of seismic network data requires computers dedicated to these tasks. Therefore, we cannot use other University computers for this purpose.
- The UUSS does not have the resources to develop the software for a network recording computer, but must instead use existing software. Software for data acquisition is highly machine specific, so the choice of software dictates the choice of hardware. Any cost savings that might appear to be gained by developing our own system would be only an illusion because of the excessive personnel costs needed to do this.

Cost Estimate

A. One-Time Costs

Network Recording Computer	
Hardware for HAWK system (with UNIX operating system included)	$112,000
Additional hardware needed to record digital data (including fabrication of specialized hardware to interface the digital telemetry with the computer)	20,000*
Development of software to add the capability to record digital data both from our own network and from the national network	40,000* (± 10,000)
Total	$172,000
Data Analysis and Research Computer	$100,000
Total one-time costs	$272,000

B. Recurring Costs

Hardware maintenance (Annual cost estimated at 10% of the initial cost of the equipment)	$22,000

*Note: The amount budgeted for the hardware and software needed to upgrade the HAWK system to record digital data totals $60,000 ± $10,000. This is a rough estimate based on discussions with NEWT, Inc., which developed the original version of the HAWK system. For reference, another company quoted us a price of $51,125 for a PC-based system capable of recording continuous digital data from 16 3-component stations. This price included $30,000 for software and $5,525 for system integration and test. The software for the PC-based system does recording, triggering, and file management only. In light of this price quote, it does not seem unreasonable to budget $60,000 ± $10,000 for hardware and software to upgrade the HAWK system to record both continuously telemetered digital data and national network data.

Part II. Expanded Access to State Microwave System

There are various options for the telemetry of data from remote digital stations to our central recording lab, including possible use of the satellite telemetry scheme being developed for the U.S. National Seismic Network (Fig. A-2). In Utah there is a state-operated microwave system (Fig. A-6) that is adequately statewide, underutilized, and which we can use at relatively low cost.

We've determined that digital telemetry over our state microwave system is the most practical and cost-effective way for us to proceed over the long run. Importantly, the ground-based microwave system will allow continuous, real-time data telemetry and recording. Satellite telemetry by contrast would require high costs for establishing each ground node, would not allow continuous digital telemetry (without prohibitive cost), and would involve higher annual telemetry costs. We already transmit data from 45 seismic-channel components in our network over the microwave system and have an excellent working relationship with its operators.

Establishing a microwave node at the UUSS recording center: Currently there is a cost problem in our telemetry scheme in that microwave telemetry channels end several miles from our recording center and have to be carried on their final leg by commercial telephone circuits. We now pay approximately $12,000 per year (including overhead on external funding) to carry six telemetry channels from the nearest microwave drop-off to our campus only five miles away.

Increased channel use that we envision on the state microwave system will compel establishing a microwave node at our recording center. We anticipate using as many as 24 channels for which a final microwave leg to our recording center could cost as much as $75,000. Discussions are underway exploring other uses for such a link (e.g., connecting a new supercomputer on campus to the state microwave system). Resolution of this cost issue may ultimately involve various parties, but we feel that establishing a microwave node at our recording center is a key step in our instrumentation plan. The node would be extremely valuable for a link to the emergency operating center of CEM (see Element D). It would also eliminate operational problems in our dealings with commercial telephone companies, which can be complex and involve significant delays.

Extra channels on state microwave system: We now use 6 channels on the state microwave system and pay $7,500 per year for extensive data transmission service. Our instrumentation plan would require the use of 18 additional channels, which would involve start-up costs of less than $500 per channel and recording costs of about $1000 to $2000 per year for each channel. We've been assured by the Utah Department of Public Safety that the channel space would be readily available. As a practical matter, each three-component digital station would require one dedicated channel for continuous data telemetry.

Part III. Upgrading and Expansion of Selected Network Stations

We've devised a scheme for accomplishing a significant upgrading of our existing analog network that will involve five separate steps:

- Step 2 (Fig. A-5)—Establishing a prototype 3-component broadband digital station at an existing site within line-of-sight radio transmission of our recording center.
- Step 5 (Fig. A-5)—Upgrading of 9 more existing stations, after the prototype has verified the performance of specific equipment components to 3-component broadband digital operation. (See circumscribed solid triangles in Fig. A-7.)
- Step 6 (Fig. A-5)—Installation of 10 new single-component stations along the Wasatch fault using existing Geotech S-13 vertical component seismometers and new digital electronics. (See non-circumscribed solid triangles in Fig. A-7.)
- Step 7 (Fig. A-5)—Moving 3-component analog equipment, made available by Steps 2 and 5, to 7 new sites near nodes of the state microwave system and in areas of presently poor seismographic coverage. (See open circles in Fig. A-7.)
- Step 8 (Fig. A-5)—Eventual upgrading of the latter 7 stations to 3-component broadband digital operation.

Part IIIA. Upgrading of 10 Stations to Broadband Digital Stations

Statement of Problem

- Waveform data recorded by the Utah seismic network are clipped (off scale) at most stations within 100 km of earthquakes larger than magnitude 3 and within 300 km of earthquakes larger than magnitude 4. Clipping occurs because the analog telemetry system used to transmit signals from remote seismic stations to the central recording facility has a dynamic range of only 40 to 60 db (a factor of 100 to 1000). This dynamic range is much smaller than the dynamic range of seismic waves from local earthquakes, which, in terms of acceleration, is approximately 160 db (a factor of 10^8) for the magnitude range 1.5 to 7.5 (Fig. A-8).
- The sparse network of 25 strong motion accelerographs in Utah (operated by federal agencies) can record on-scale ground motions from the largest earthquakes that are expected to occur in Utah (~M 7.5), but cannot record ground motion from earthquakes smaller than about magnitude 4.5 to 5, even when they are very close. These accelerographs and the stations of the Utah seismic network are the only earthquake recording instrumentation in Utah except for the World Wide Standardized Seismo-

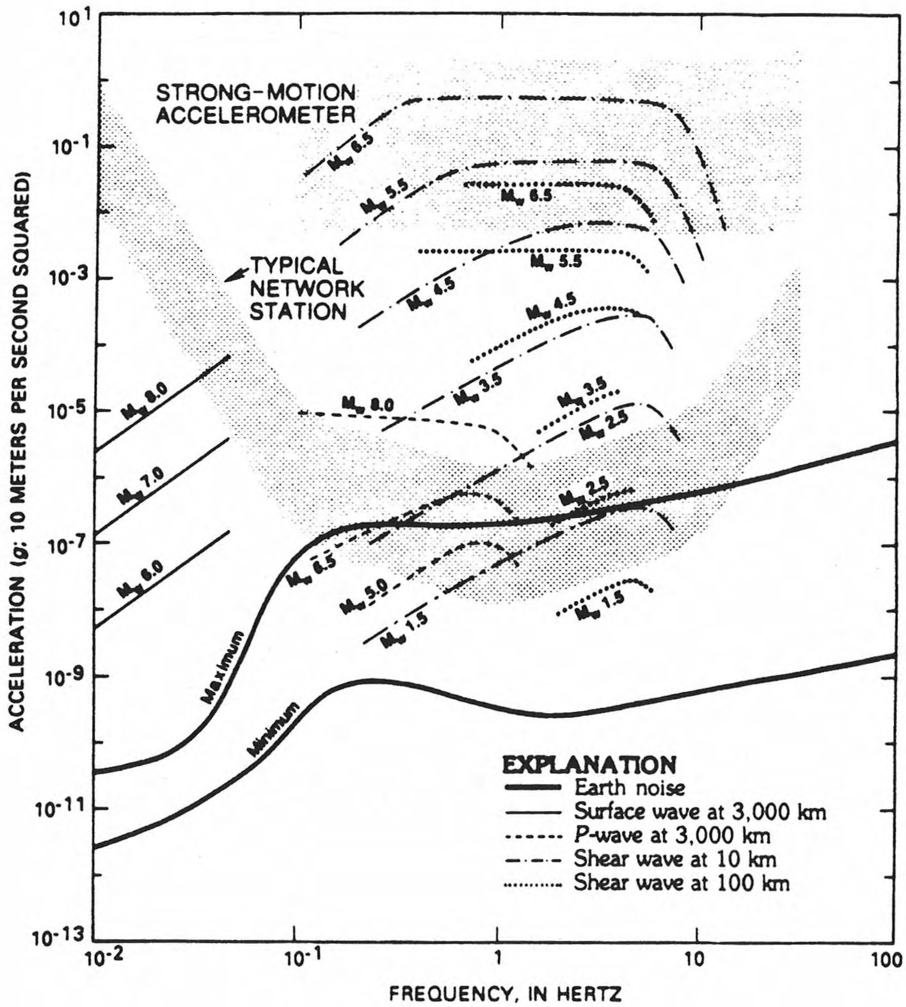


Figure A-8.

Dynamic range versus frequency for a typical regional network station and a typical strong motion station. Also shown are typical levels of earth noise and the expected levels of ground motion for different seismic arrivals from earthquakes of different sizes recorded at different distances. The amplitudes plotted correspond to time domain amplitudes for signals filtered with one-octave wide bandpass filters. (From T.H. Heaton et al., National Seismic System Science Plan, U.S. Geological Survey Circular 1031, 1989) graph Network station at Dugway, Utah, and a single high quality station near the Utah-Arizona border operated by the Lawrence Livermore National Laboratory. Consequently, there is a gap in the recording of ground motion in Utah that amounts to more than three orders of magnitude, in units of ground acceleration (Fig. A-8).

- The long period limit to the bandwidth of the Utah seismic network data is typically 2 to 3 seconds. Earthquakes larger than about magnitude 4.5 can have durations that exceed 2 to 3 seconds. Thus, the Utah seismic network cannot record the complete frequency spectrum of seismic waves from earthquakes larger than about magnitude 4.5, which are precisely the earthquakes of greatest interest.
- The analog telemetry system introduces an excessive amount of noise into the data. For most of our data, this telemetry noise exceeds the earth noise at the recording site.

Specific Goal

- To upgrade selected stations in the Utah seismic network so that three-component recordings of ground motion over an amplitude range of $\sim 10^{-8}$ to 0.1 g and a frequency range of $\sim$0.03 to 30 Hz can be obtained from at least two recording sites within 100 km of any earthquake within the main part of the Intermountain Seismic Belt in Utah. This amplitude and frequency range covers nearly the entire range of interest for local earthquakes (Fig. A-8). The minimum detectable ground acceleration of 10^{-8} g planned for these stations is comparable to that of most of the other stations within the Utah network, given the noise levels inherent in the analog telemetry. The maximum ground acceleration of 0.1 g that could be recorded by these stations would be exceeded only very rarely, for example within 10 to 20 km of a magnitude 5 earthquake or within 50 to 100 km of a magnitude 7.5 earthquake. (Colocation of a digital strong motion accelerograph at each of these stations would enable the recording of ground motions at these sites covering the entire frequency and amplitude range of interest.)

Instrumentation Plan for Upgrading 10 Stations to Broadband Digital Stations

We propose to upgrade ten stations of the Utah seismic network to high quality, three-component, broadband, digital telemetry stations having a dynamic range of 136 db (6×10^6), a bandwidth of at least 0.03 to 30 Hz, and the sensitivity needed to record ground motions as small as 10^{-8} g (Fig. A-8). The technology to do this is readily available. Seismometer signals spanning a dynamic range of 136 db can be sent from a remote station to the central recording lab if the seismometer output is digitized on site with either a 24-bit digitizer or a 16-bit digitizer with gain ranging and then transmitted on a digital telemetry link. The microwave communications system operated by the State of Utah provides a convenient and cost effective means to transmit this digital data. With available technology, it is possible to send digital data from three channels (one for each of three orthogonal components of ground motion) sampled at a rate of up to 120 samples/sec over a single channel of this microwave system. Digital telemetry will not only improve the dynamic range of the data, but (with appropriate error correction) will also greatly reduce the amount of noise introduced into the data during transmission. The hardware required for the digitization and digital telemetry can either be purchased commercially or fabricated by our electronics engineer.

Seismometers with the required dynamic range, bandwidth and sensitivity are available from at least two different vendors. The Guralp CMG-4T triaxial seismometer ($9500) has dual-gain velocity and acceleration outputs with a flat velocity response from 0.03 to 100 Hz and a flat acceleration response from 0 to 100 Hz. The dynamic range of this seismometer is 145 db and the clip level can be set between 0.1 and 2 g. Operation of a 0.1g CMG-4T with a 136 db digital telemetry link would enable recording of ground accelerations within the desired range of 10^{-8} to 0.1 g. The Streckeisen STS-2 triaxial seismometer ($12,500) is a velocity transducer which has a flat velocity response from 0.008 to 50 Hz. The dynamic range of the STS-2 is 135 db in the frequency range 1 to 10 Hz and 140 to 160 db at lower frequencies. The clip level is 1.3 cm/sec, which corresponds roughly to an acceleration of 0.08 g at 10 Hz and 0.008 g at 1 Hz.

In order to get the best performance out of these broadband seismometers, it will be necessary to place them in specially constructed concrete vaults or in abandoned mine tunnels. Such facilities already exist at five stations within the Utah network, but vaults will have to be constructed at the other five selected sites.

The estimated cost for a digital 3-component station is $11,000 for sensors, $3,000 for a 3-component digitizer, $1,150 for a radio pair, $3,400 for a 9600 baud modem pair, and $2,000 for miscellaneous site hardware. At sites where a vault must be constructed, there will be an additional cost of approximately $6,000. The total cost for one station will therefore be about $21,000 if a vault is available and $27,000 if a vault must be constructed.

Justification for Instrumentation Plan for Upgrading

- The stations of the Utah seismic network can record seismic waves on scale only for small or distant earthquakes. In particular, seismic waves from earthquakes larger than magnitude 4 are off scale at most stations located within distances of a few hundred kilometers. Every time a larger earthquake occurs in Utah, valuable data that would contribute to our understanding of earthquakes in Utah are lost forever because the appropriate instrumentation is not in place to collect it.

- The small dynamic range and bandwidth of the data from the Utah seismic network severely limits the usefulness of these data for earthquake research. Much more effective research on Utah earthquakes could be done using data from broadband, wide dynamic range stations like the ones that we are proposing to install.
- The proposed broadband digital stations would be capable of recording seismic waves with peak accelerations of up to 0.1 g. Good quality recordings of stronger ground motions can be obtained from strong motion accelerographs. Thus, the upgraded stations would close the large gap that now exists between ground motions that can be recorded by stations of the Utah seismic network and those that can be recorded by strong motion instruments.
- In the aftermath of a large earthquake, data from the ten broadband digital stations could be used to estimate the approximate distribution of ground shaking above the usual damage threshold of 0.1 g. This information would be of great value to emergency response personnel.
- There are good scientific reasons for recording both small and large earthquakes with the same instrumentation at the same site. In particular, techniques have been developed that make use of waveforms of small earthquakes to correct waveforms of large earthquakes for the complications introduced by the effects of wave propagation through complex geologic structure.
- The Utah seismic network could record larger earthquakes on scale if the seismic stations were operated at lower gain levels, but this would degrade the earthquake detection and location capability of the network. Both low-gain and high-gain channels are recorded from the vertical component seismometers at seven stations of the network. However, the low-gain channels typically have a gain that is only 30 db (a factor of 32) lower than the gain on the high-gain channels. Because the dynamic range of each data channel is so limited, it is not possible to increase the gain differences between low-gain and high-gain channels without sacrificing the continuity in recording between the two channels.
- Digital telemetry over the state microwave system is by far the most practical and cost effective means to obtain high quality recordings of data from the ten stations in the network that we are proposing to upgrade. Other options that we have considered are satellite telemetry through the national seismic system and on-site recording with data retrieval by telephone dialup. The site hardware needed for telemetry via the state microwave system costs at least a factor of three less than that needed for satel-

lite telemetry and a factor of two less than that needed for on-site recording. Furthermore, satellite telemetry requires that commercial power be available at the site, and this is the case at hardly any of our stations. Retrieval of data by telephone requires that telephone service be available at the site, and again this is the case at hardly any of our stations. Finally, the cost of a telephone line and the long distance calls needed to retrieve the data would be at least comparable to and probably greater than our rental cost for a line on the state microwave system, which is $300 to $1200 annually, depending on the length of the line.

Part IIIB. Establishing 10 New Single-Component Stations Along the Wasatch Fault

Statement of Problem

Our existing station distribution along the Wasatch Front is relatively sparse compared to that along major active faults in California, and the station spacing allows reliable focal-depth resolution for fewer than 10 percent of the located earthquakes.

Specific Goal

To increase hypocentral resolution along the Wasatch fault by increasing the density of high-quality stations at relatively low cost.

Instrumentation Plan and Cost for 10 New Stations Along the Wasatch Fault

We propose to augment our station coverage of the Wasatch fault by installing 10 vertical-component stations at new sites along the urban corridor. We'll use existing S-13 Geotech seismometers (assuming they are made available by buying new sensors for portable seismographs—Element C) that have a replacement value of $2,400 each. Instead of installing analog VCO/preamp's, we want to install digital telemetry that requires digitizer/modem and new VHF radios. For a single-component station, the estimated cost for digitizer and a modem pair would be $1,000 for a sampling rate of 150 samples/sec and transmission at 2,400 band.

The one-time cost for each new station would be $3,600, excluding the available sensor, and including necessary UHF radio links. This cost would be virtually identical to that for installing standard analog electronics. The total package cost would be $36,000 plus one-time start-up costs of $4,000 for 8 new microwave channels. Recurring costs would involve routine station repair and maintenance and about $3,000 to $4,000 per year for microwave telemetry (assuming a dropoff at one recording center).

Justification for New Stations Along the Wasatch Fault

- The Wasatch fault is a first-order target for seismic surveillance with our seismic network. Low levels of background seismicity on the Wasatch fault have made it an unattractive target for portable-array recording; continuous long-term recording by permanent-network stations is the preferred option.
- Despite the compelling need to instrument the Wasatch fault, our network size has remained at the same level since the late 1970's when it became apparent that neither Federal nor State funding was adequate to meet recurring costs of network expansion. Any plan for upgrading our network, however, has to give a high priority to the Wasatch fault.

Part IIIC. Establishing 7 New 3-Component Regional Stations in Utah

Statement of Problem

Existing seismographic coverage both of Utah's main seismic belt and of distal seismically active parts of the state is inadequate (Fig. A-7).

Specific Goal

With state support and encouragement, make some reasonable progress in expanding reigonal seismographic coverage in Utah.

Instrumentation Plan and Cost for 7 New Regional Stations

The upgrading of sensors and site electronics at 10 of our existing seismic stations (Steps 2 and 5, Fig. A-5) coincidentally will free up 3-component Geotech S-13 sensors and associated VCO-preamps at 7 of the stations. We propose to move this equipment to 7 new sites distributed broadly in Utah (open circles, Fig. A-7) as a strategic first step in establishing more high-quality stations in Utah.

Our plan is to select sites that will complement our existing station distribution and improve regional uniformity of coverage. By picking sites within line-of-sight of nodes of our state microwave system, we can set the stage for subsequent digital telemetry. One-time costs could be as much as $6,000 per station for constructing durable vaults at the remote sites for the security and controlled environment desirable for high-quality 3-component regional stations. Microwave channel space in effect is already accounted for because the equipment is simply being moved from already-operational sites.

Eventual conversion to 3-component broadband sensing and digital telemetry would cost $9,500-$12,500 per station for sensors and $6,400 per station for a digitizer and

9600-band modem pair leading to a price tag of about $17,400 per station for hardware upgrading. Requirements for having a dedicated microwave channel for each three-componenet digital station would cost about $10,000 per year for recurring microwave costs.

Justification

The expanded areal distribution of 3-component broadband digital stations in Utah resulting from this effort would serve numerous scientific and practical goals that motivate the upgrading of regional seismic networks (as described in detail in Attachment No. 8).

Part IV. Interface with U.S. National Network

In our foreword, we described the desired national goal of integrating regional seismic networks with the U.S. National Seismic Network (USNSN) to form a National Seismic System (detailed discussion appears in Attachment No. 8). This inherently requires an interface between the recording centers of regional seismic networks and the USNSN master station in Golden, Colorado, through a satellite link. (A satellite dish and associated electronics would have to be installed at each regional network recording center.)

Note that the national distribution of USNSN stations assumes that funding will somehow become available to install three USNSN stations (at a cost of $50,000 per station) within Utah (Figs. A-2 and A-3). The estimated cost for the satellite telemetry node at our recording center would be $35,000 to $45,000. In our flowchart in Figure A-5 we gave the establishing of the USNSN satellite link lowest priority, assuming that funding for the USNSN stations in Utah and the satellite interface would be ultimately provided by the USGS when federal funding becomes available for the entire USNSN project.

There clearly will be many benefits to reciprocal exchange of digital data streams between the USNSN master station and our recording center. In terms of funding priorities, however, all of the sequential parts of our proposed plan would be more important to Utah's immediate needs than Step No. 9 (Fig. A-5)—the establishing of the satellite link.

Appendix A-1

University of Utah Regional Seismic Network

Appendix Figure 1 and Appendix Table 1 summarize essential information for the current 80-station University of Utah seismic network. (Appendix Figure 3 summarizes cost information.) Basically, the network consists of 45 telemetry stations focused on the Wasatch Front area, an additional 12 stations that provide expanded coverage of the Utah region (chiefly central and southwestern Utah), and another 23 stations covering the continuation of the ISB from northern-most Utah to Yellowstone Park. Appendix Table 1 indicates that 26 of the 80 stations are maintained by other operators. The University of Utah currently handles field repair and maintenance of 54 stations, 42 of which are sponsored by the USGS.

At the University of Utah, approximately 2200 seismic events are detected and analyzed per year. These include teleseisms, regional earthquakes, and blasts. During the four-year period July 1984 through June 1989, approximately 1100 local earthquakes in the ISB were located annually. Of these, about 500 per year were in the Utah region and 375 were in the Wasatch Front region. On the average, 20 earthquakes of $M_L \geq 3.0$ and 15 felt earthquakes occur every year within that part of the ISB monitored by the University of Utah seismic network.

Appendix Figure 2, although not completely up-to-date, illustrates the overall telemetry scheme of the University of Utah regional seismic network. Solid lines indicate radio links; the dashed lines, microwave (M) or telephone (T) links. There are very few telephone links remaining in the telemetry system. The major exception is the group of 6 telephone lines that carry data from 48 stations from the Utah Department of Public Safety microwave installation on Ensign Peak, overlooking Salt Lake City, to our central recording lab on the University of Utah campus.

The development of our telemetered seismic network has consistently focused on quality. Field operations have involved careful site selection and attention to reliable instrument performance. In addition to station-component quality and reliability, efforts are continuing to complete in-situ calibration of our entire network—an essential requirement for extracting quantitative information from the waveform analysis of digitally-recorded seismograms.

UNIVERSITY OF UTAH REGIONAL SEISMIC NETWORK
Operating Seismograph Stations: August, 1989

	Name	Lat(N)	Long(W)	Elev (m)	Seismometer	Electronics	Sponsor
	AIUT	40° 51.35′	112° 10.53′	1334	L4	J302	USGS
	ANU	41° 02.38′	112° 13.90′	1353	L4	J302	USGS
	ARUT	37° 47.28′	113° 26.42′	1646	L4	J302	Utah
	BBUT	40° 44.73′	112° 00.67′	1291	L4C	J302	USGS
	BDU	40° 52.45′	111° 32.04′	2198	L4	J302	USGS
	BEI	42° 07.00′	111° 46.94′	1859	L4	J302	USGS
	BMUT	41° 57.49′	111° 14.05′	2243	S13	Geotech	USGS
*	BW06	42° 46.66′	109° 33.33′	2200	(NEIC)		
*	CBTI	43° 23.01′	112° 54.49′	1690	(INEL)		
	CCU	37° 40.52′	113° 04.11′	1775	Ben 14	J302	Utah
	CMU	39° 10.28′	110° 37.16′	2332	L4	Develco	Utah
	CPU	40° 40.34′	112° 11.78′	2377	L4C	Geotech	USGS
*	CRBI	43° 49.82′	112° 38.07′	1543	(INEL)		
	CWU	40° 26.75′	112° 06.13′	1945	L4	J302	USGS
	DAU	40° 24.75′	111° 15.35′	2771	S13	Geotech	USGS,USBR
	DCU	40° 24.82′	111° 31.61′	1829	L4	U of U	USGS,USBR
*	DLM	37° 36.35′	114° 44.33′	1730	(USGS)		
+++	DUG	40° 11.70′	112° 48.80′	1477	S13,WA	Geotech	Utah,USGS
	DWU	38° 06.32′	112° 59.85′	2270	S13	Develco	Utah
++	EMUT	39° 48.84′	110° 48.92′	2268	S13	U of U	USGS
	EPU	41° 23.49′	112° 24.53′	1436	S13	J302	USGS
	FLU	39° 22.69′	112° 10.23′	1950	18300	Develco	USGS
	FPU	41° 01.58′	111° 50.21′	2816	L4	Develco	USGS
	FSU	39° 43.35′	113° 23.48′	1487	Ben 14	Develco	Utah
*	GBI	43° 59.25′	112° 03.80′	1561	(INEL)		
+	GMU	40° 34.53′	111° 45.79′	1829	Ben 14	J302	USGS
	GZU	41° 25.53′	111° 58.50′	2646	S13	Geotech	USGS
	HDU	41° 48.27′	111° 45.89′	1853	18300	J302	USGS
*	HPI	43° 42.68′	113° 05.90′	2597	(INEL)		
‡	HONU	41° 36.60′	111° 55.02′	1515	L4C	J302	USGS
	HTU	40° 40.52′	111° 13.21′	2576	L4	J302	USGS
++	HVU	41° 46.78′	112° 46.50′	1609	S13	U of U	USGS
	IMU	38° 37.99′	113° 09.50′	1833	L4C	Develco	Utah
*	IMW	43° 53.82′	110° 56.35′	2646	(Ricks College)		
++	JLU	40° 36.11′	111° 26.95′	2304	S13	U of U	USBR
	LSUT	41° 41.09′	111° 33.45′	2225	S13	Geotech	USGS
	LTU	41° 35.51′	112° 14.83′	1585	L4	J302	USGS
	LVU	39° 29.50′	111° 49.60′	2530	L4	J302	USGS
	MCU	41° 27.70′	111° 30.45′	2664	18300	Develco	USGS
	MLI	42° 01.61′	112° 07.53′	1896	L4	J302	USGS
	MMU	38° 11.91′	111° 17.66′	2387	S13	Develco	Utah
	MOUT	41° 11.94′	111° 52.73′	2743	S13	Geotech	USGS
	MSU	38° 30.80′	112° 10.45′	2141	18300	Geotech	Utah
	MTUT	41° 42.55′	112° 27.28′	1373	L4	Develco	USGS
	NLU	39° 57.29′	112° 04.50′	2036	Ben 14	Develco	USGS
++	NMUT	38° 30.99′	112° 51.00′	1853	S13	U of U	Utah
	NPI	42° 08.84′	112° 31.10′	1640	L4	Develco	USGS

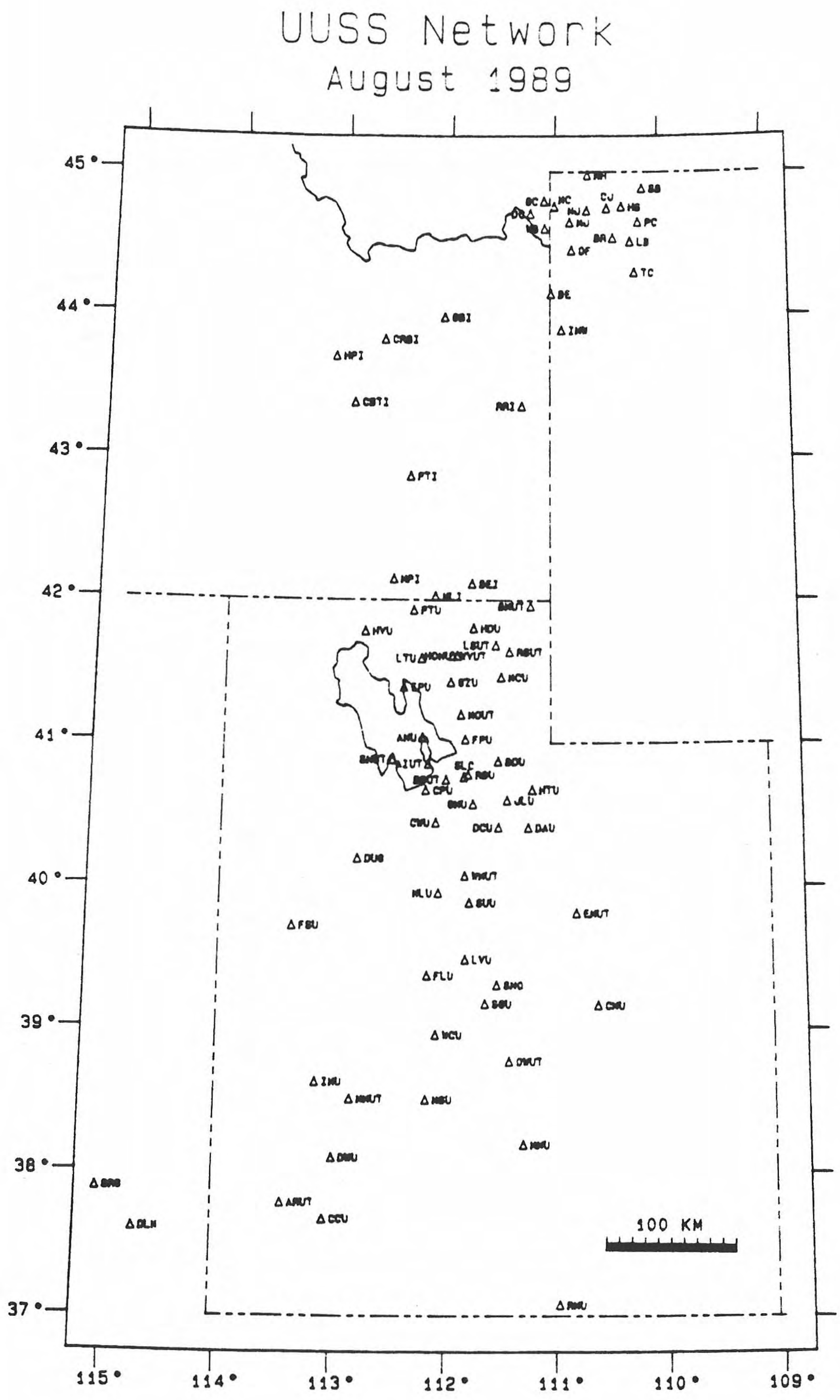
Appendix (A) Table 1.

	Name	Lat(N)	Long(W)	Elev (m)	Seismometer	Electronics	Sponsor
	OWUT	38° 46.80′	111° 25.42′	2568	L4	Develco	USGS
	PTI	42° 52.22′	112° 22.21′	1670	L4	J302	USGS
	PTU	41° 55.76′	112° 19.48′	2192	L4	ER	USGS
	RBU	40° 46.85′	111° 48.50′	1676	S13	J302	USGS
	RMU	37° 04.56′	110° 58.20′	1536	L4	Geotech	Utah
*	RRI	43° 21.84′	111° 19.14′	2566	(Ricks College)		
	RSUT	41° 38.31′	111° 25.90′	2682	S13	Geotech	USGS
	SGU	39° 10.97′	111° 38.60′	2365	18300	ER	USGS
	SLC	40° 45.83′	111° 50.87′	1423	WA Type	Hard Wire	Utah
*	SNO	39° 18.86′	111° 32.28′	2446	(Snow College)		
	SNUT	40° 53.14′	112° 30.54′	1652	18300	J302	USGS
*	SRG	37° 52.93′	115° 04.08′	1645	(USGS)		
	SUU	39° 53.32′	111° 47.50′	1987	18300	J302	USGS
	TMUT	41° 41.85′	112° 20.55′	1715	L4	Develco	USGS
	WCU	38° 57.88′	112° 05.40′	2714	18300	ER	USGS
	WMUT	40° 04.60′	111° 50.00′	1981	L4	J302	USGS
	WVUT	41° 36.61′	111° 57.55′	1828	L4	J302	USGS
*	YPBE	44° 08.97′	111° 02.34′	1966	(USGS)		
*	YPBR	44° 32.20′	110° 26.37′	2383	(USGS)		
*	YPCJ	44° 44.63′	110° 29.85′	2426	(USGS)		
*	YPDC	44° 42.57′	111° 14.38′	2025	(USGS)		
*	YPGC	44° 47.77′	111° 06.39′	2075	(USGS)		
*	YPHS	44° 45.33′	110° 21.24′	2621	(USGS)		
*	YPLB	44° 30.68′	110° 16.32′	2565	(USGS)		
*	YPMC	44° 45.56′	111° 00.37′	2073	(USGS)		
*	YPMH	44° 58.62′	110° 41.12′	1781	(USGS)		
*	YPMJ	44° 38.90′	110° 51.52′	2111	(USGS)		
*	YPNJ	44° 43.82′	110° 41.58′	2290	(USGS)		
*	YPOF	44° 27.15′	110° 50.48′	2260	(USGS)		
*	YPPC	44° 38.84′	110° 11.58′	2939	(USGS)		
*	YPSB	44° 53.04′	110° 09.06′	2072	(USGS)		
*	YPTC	44° 17.79′	110° 13.92′	2360	(USGS)		
*	YPWB	44° 36.35′	111° 06.05′	2310	(USGS)		

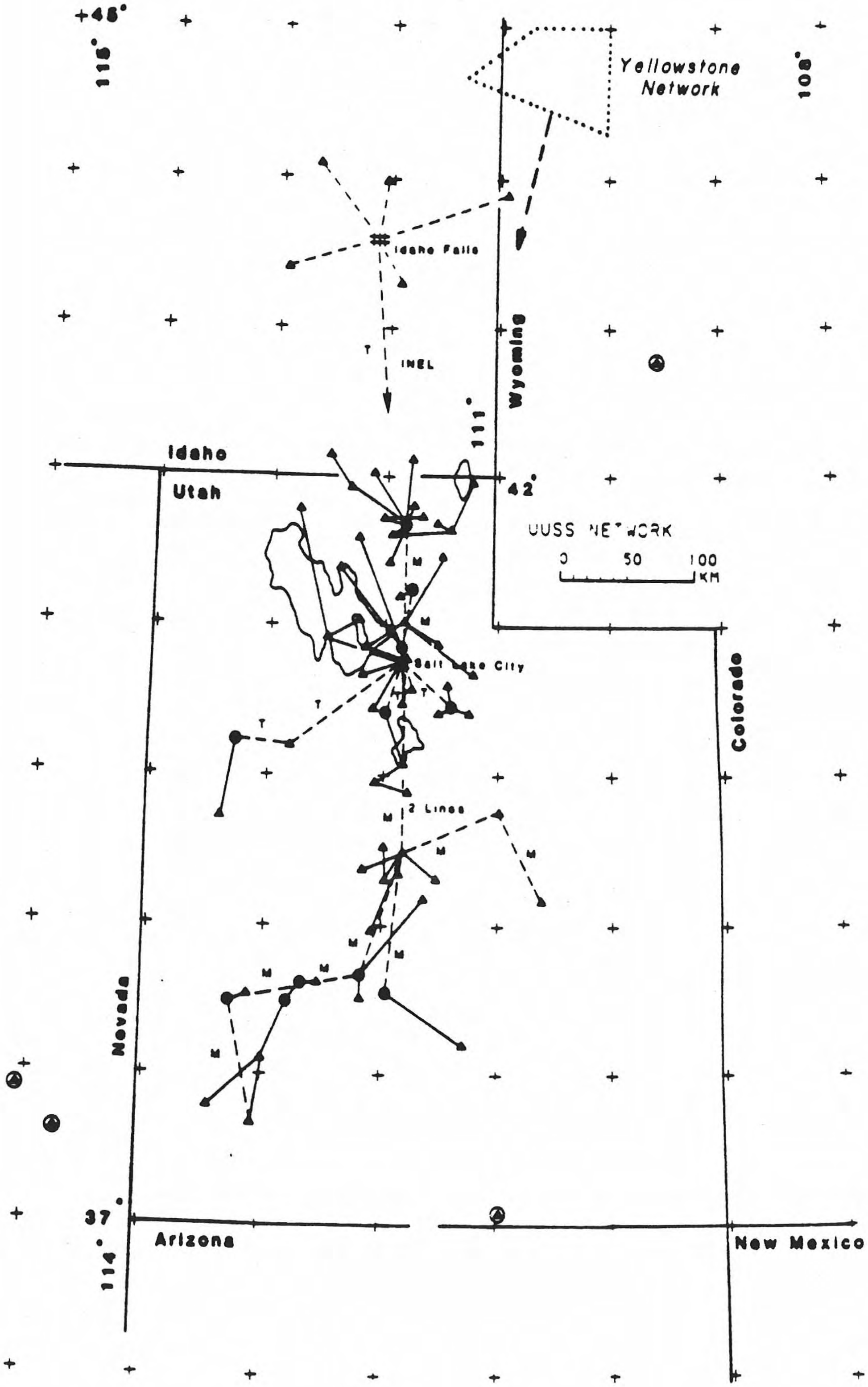
KEY

* Indicates station operated by other agency and recorded as part of University of Utah regional seismic network.
\+ Indicates 3-component station (one vertical, two horizontals)
++ Indicates 4-component station (high- and low-gain verticals plus two horizontals)
+++Indicates 6-component station (three high-gain, three low-gain)

BEN 14	—	Benioff 14 kg	INEL	—	Idaho National Engineering Laboratory
ER	—	Emhiser Rand	USBR	—	U.S. Bureau of Reclamation
J302	—	USGS design	USGS	—	U.S. Geological Survey
L4C	—	Mark Products L4	Utah	—	State of Utah
S13	—	Geotech S13 or 18300			
U of U	—	University of Utah			
WA	—	Wood Anderson			



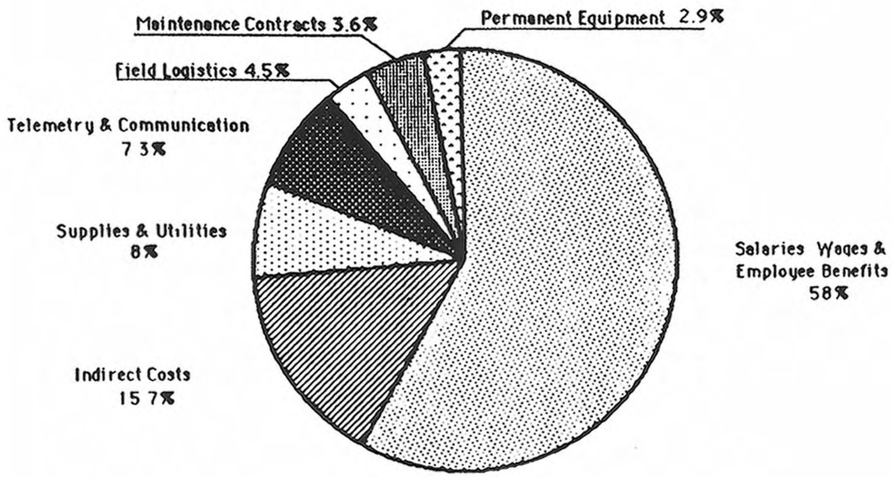
Appendix (A) Figure 1.

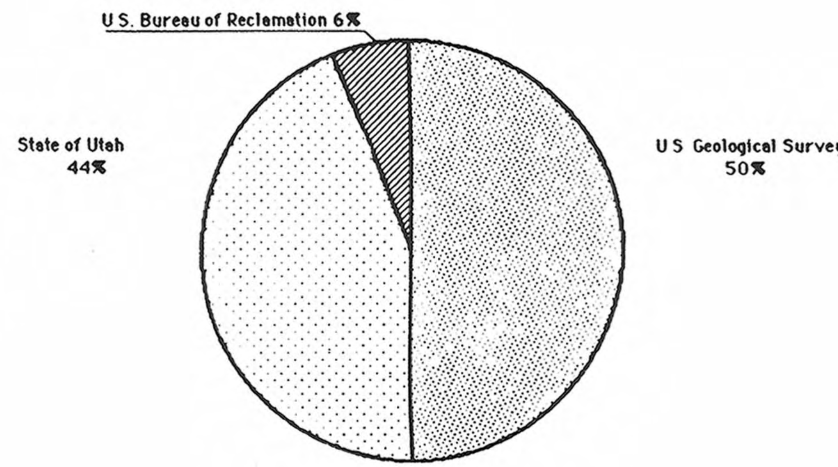


Appendix (A) Figure 2.

UNIVERSITY OF UTAH SEISMOGRAPH STATIONS

Annual Cost for Seismic Network Operations (Exclusive of Research) in Utah Region Only, 1988-89





EXPENDITURES

Salaries, Wages & Employee Benefits	$216,197
Indirect Costs	58,447
Supplies & Utilities	29,962
Telemetry & Communications	27,045
Field Logistics	16,881
Maintenance Contracts	13,322
Permanent Equipment	10,774
	$372,628

REVENUE

U.S. Geological Survey		
• Regular network budget	$165,000	
• Computer maintenance contract	8,220	
• One-time permanent equipment award	10,774	
• Dugway WWSSN contribution	2,508	
		$186,502
State of Utah (77% of $217,700 line-item appropriation)		165,126
U.S. Bureau of Reclamation		21,000
		$372,628

Appendix (A) Figure 3.

Appendix A-2

Requirements for New Network Recording Computer
August 7, 1989

(Dedicated to real-time data acquisition and routine processing)

1. Capability of digital recording in real time of incoming seismic data from 256 channels at a sampling rate of at least 100 samples/sec.

2. Capability to simultaneously record data from analog telemetry links through an analog to digital converter and data from digital telemetry links through a high speed parallel digital interface. The system should allow different sampling rates for analog and digital data. The relative number of analog and digital channels should be flexible to allow for future upgrading of analog stations to digital stations.

3. Capability to record digital data from national network stations (when such data become available). Data from these stations will arrive via satellite telemetry with some time delay relative to the local network data, and may not have the same sampling rate as the local network data.

4. Accessible sampling clock to use for synchronization of sampling clocks at remote seismic stations.

5. Software to detect seismic events in real time, save the waveform data from these events on disk for processing, and automatically write the waveform data to backup tapes.

6. Software to automatically and in near real time identify local earthquakes, determine earthquake locations and magnitudes, and update files containing reduced data for these earthquakes, including an earthquake catalog.

7. Ability to generate an alarm (via telephone or pagers) in the event of a significant earthquake, system malfunction, or impending disk overflow.

8. Modems and terminal ports to allow seismologists or other trained personnel to check on recent seismic activity from locations outside of the recording lab. (This will necessitate some security software.)

9. Software for interactive review and revision of automatically determined earthquake locations and magnitudes.

10. Minimum of two graphics terminals for use in interactive data analysis.

11. High capacity tape drive for automatic backup of raw data.

12. Laser disk drive for permanent archiving of processed data.

13. Standard tape drive (9-track recording at densities of 1600 and 6250 bpi on 1/2 inch tape), for reading old archive tapes and exchanging data.

14. Printer/plotter device for output of text and graphics.

15. Private network link to another computer in the Seismograph Stations that can be used for further analysis of data from the seismic network, seismological research, and word processing.

16. Software and hardware available for use with minimal modifications.

17. Strong preference for UNIX operating system, for compatibility with existing computer available within the Department of Geology and Geophysics and the College of Mines and Earth Sciences.

Appendix A-3

Requirements for New Data Analysis and Research Computer
August 8, 1989

(The computer described below is designed to meet only the needs of those engaged in analysis of seismic network data and earthquake research. Use of this machine by a significantly larger group would necessitate more hardware than specified here.)

1. UNIX operating system, for compatibility with existing computers available within the Department of Geology and Geophysics and the College of Mines.
2. Access to terminals and peripherals (tapes drives, printers, plotters, etc.) within the Seismograph Stations.
3. Capability to handle 16 users plus at least six peripherals that connect to RS232 terminal ports (HP plotter and printers).
4. Graphics terminals for as many of the 16 users as possible, including up to two color terminals. Minimum requirement is three graphics terminals.
5. 800 Mbytes of disk space, with capability for expansion (The PDP-11/70 currently has 710 Mbytes of disk space).
6. 16-32 Mbytes of physical memory.
7. Standard tape drive (9-track recording at densities of 1600 and 6250 bpi on 1/2 inch tape).
8. Laser disk drive compatible with the one on the network recording computer.
9. High speed line printer.
10. Color printer/plotter for output of text and graphics, with appropriate software.
11. Compatibility with existing HP plotter and Apple laserwriter.
12. Software for word processing, compatible with Apple laserwriter and other printer/plotter device.
13. Network link to the University computer network.
14. Private network link to the recording computer.
15. Modem (Probably the one from the PDP-11/70 is adequate).

ELEMENT B

Strong-Motion Instrumentation For Earthquake Engineering

by J. C. Pechmann and S. S. Olig

Injury, loss of life, and loss of property most commonly are caused by the failure of man-made structures or facilities due to strong ground shaking.

Panel on Strong-Motion Instrumentation, National Research Council, 1987

THE AUTHORS

J. C. Pechmann is a Research Associate Professor in the Department of Geology and Geophysics at the University of Utah. **S. S. Olig** is a Geologist with the Utah Geological and Mineral Survey.

Revised September 5, 1989

Strong-Motion Instrumentation for Earthquake Engineering[1]

Background

Strong-motion accelerographs are rugged, low-gain seismographs designed to record the strong ground motion from large earthquakes. (For the purposes of this report, we consider strong ground motion to be ground motion having a peak acceleration greater than or equal to 0.1g, the approximate threshold for damage to weak construction.) These instruments record data on film, on magnetic tape, or in solid state memory whenever they are "triggered" by ground acceleration that exceeds a preselected threshold, usually between 0.01 and 0.1 g. Data from instruments at free-field sites (located on bedrock or on small concrete pads) and at the foundation levels of small buildings are used by seismologists and engineers to analyze strong ground motion from past earthquakes and to predict the important characteristics of strong ground motion from future earthquakes. Data recorded in large buildings (ideally from several sensors located on different floors) are used by structural engineers to evaluate the safety of buildings following large earthquakes and to study the response of buildings to ground shaking.

In Utah, instruments to record strong ground motion have been installed at 31 different sites, according to a recent compilation by William F. Case of the Utah Geological and Mineral Survey (Figure B-1, Appendix B-1). The instrumentation at all of these sites is operated by either the U.S. Geological Survey or the U.S. Bureau of Reclamation. The most elaborate installation is at the City and County building in downtown Salt Lake City, which is of exceptional interest to structural engineers because it was the first building in the world to be retrofitted with a base isolation system. Instrumentation at this building consists of two 12-channel CRA-1 recorders connected to accelerometers located throughout the building and at a free-field site near the building. Of the other sites, twenty-four are equipped with one or more standard SMA-1 strong motion accelerographs, which record on film. The instruments at the remaining 6 sites are seismoscopes, which provide records of horizontal particle motion during large earthquakes but do not provide any information about the time history of the motion.

Strong motion records have been obtained for only three Utah earthquakes, all of moderate size: the 1962 M_L 5.7 Cache Valley earthquake, recorded at an epicentral

[1]Note: This plan was originally written on August 15, 1989, and was revised on September 5, 1989, following recommendations of the Utah Policy Panel on Earthquake Instrumentation.

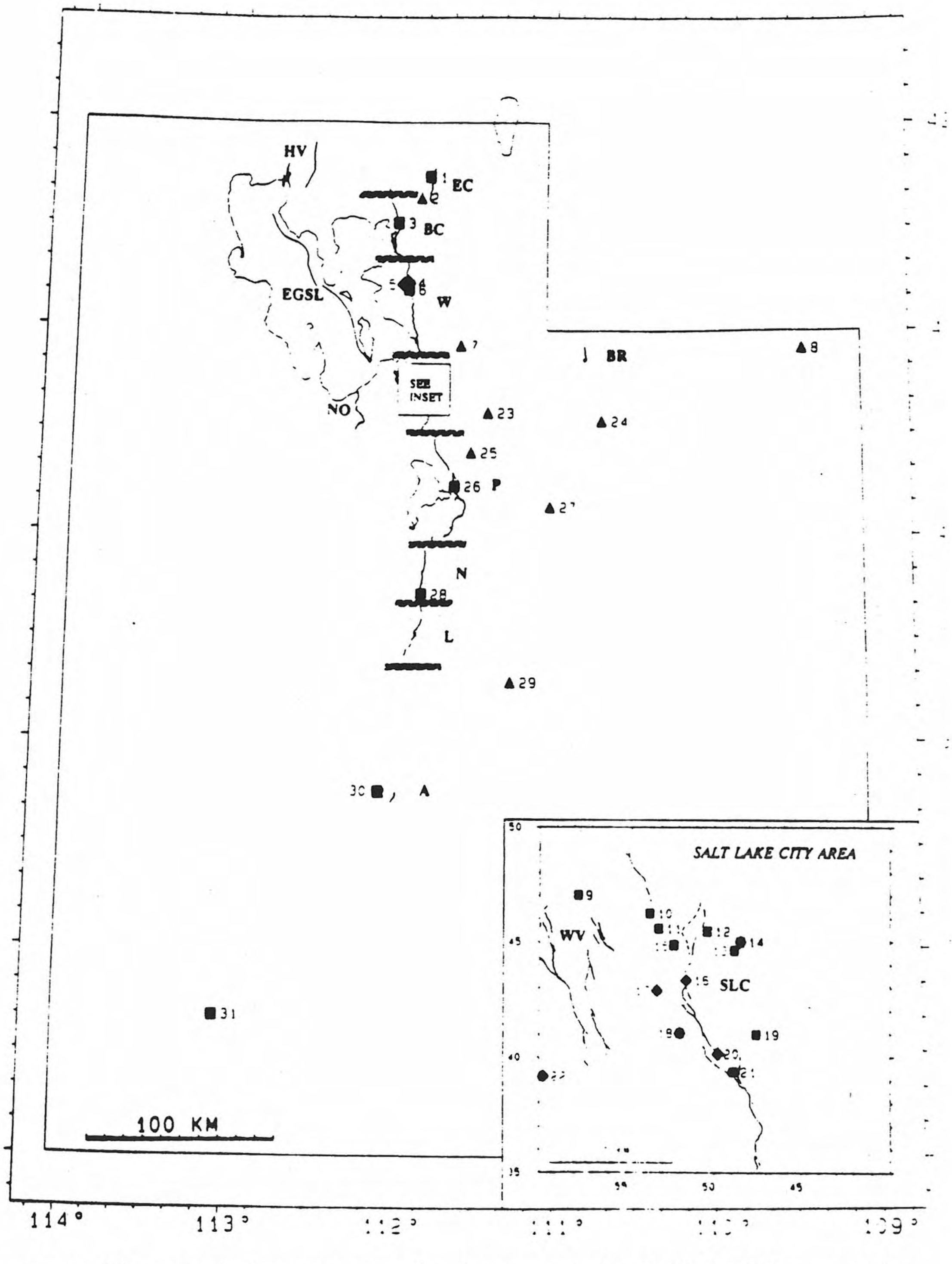


Figure B-1. Map of existing strong-motion instrument sites in Utah: (1) squares for accelerographs maintained by the U.S. Geological Survey, Menlo Park, California; (2) diamonds for seismoscopes maintained by the U.S. Geological Survey, Denver, Colorado; (3) stars for sites with both an accelerograph and a seismoscope, both maintained by the U.S. Geological Survey; and (4) triangles for accelerographs maintained by the U.S. Bureau of Reclamation, Denver, Colorado. Site numbers correspond to the list in Appendix B-1. The solid and dashed lines are the faults targeted for instrumentation. Fault labels (bold letters) are identified in Table B-1.

distance of approximately 25 km on an accelerograph in the basement of the Old Main building on the campus of Utah State University in Logan; the 1988 M_L 5.3 San Rafael Swell earthquake, recorded at an epicentral distance of 42 km on accelerographs located on the crest and midslope of the Joe's Valley Dam (location 29, Figure B-1 and Appendix B-1); and the 1989 M_L 5.4 Salina earthquake, recorded at an epicentral distance of 60 km on accelerographs located on the Joe's Valley Dam and on rock at the base of the dam. The 1983 M_s 7.3 Borah Peak, Idaho, earthquake occurred in an area that is tectonically similar to the Wasatch Front region, and was recorded on 13 accelerographs at the Idaho National Engineering Laboratory. However, all of these instruments were located at distances of 90 km or more from the nearest part of the fault rupture.

Statement of Problem

The problem in Utah is simple: there is a lack of data on strong ground motions from past earthquakes that can be used to predict expected ground motions from future earthquakes. Engineers need to know these expected ground motions in order to design earthquake-resistant structures. Planners need accurate and detailed information on ground shaking hazards for purposes of planning and zoning.

In 1980, at a time when there were only ten strong motion accelerographs at six different sites in Utah, a report by the now-disbanded Seismic Safety Advisory Council of the State of Utah recommended that the state fund the installation and maintenance of a minimum of 17 new accelerographs at 11 different sites. This program was never funded, but in the succeeding nine years federal agencies installed accelerographs at 19 additional sites and seismoscopes at 6 sites. The geographic distribution of these new sites is similar to the distribution of the sites proposed by the Seismic Safety Advisory Council. One might therefore be tempted to conclude that the existing strong motion instrumentation in Utah is adequate, but for several reasons we believe that this is not the case:

- *Sparse present coverage.* The number of existing strong motion instruments in Utah is still very small (25 installations, excluding seismoscopes), especially when compared to the more than 1000 instruments in California (not including instruments installed by building owners to meet building code requirements).
- *Lack of data from Utah earthquakes.* Very few records of strong ground motion have been obtained for earthquakes in Utah and elsewhere in the Intermountain seismic belt. Consequently, it is necessary to use strong motion records from

earthquakes in California and elsewhere to guide predictions of strong ground motion for Utah earthquakes. The resulting predictions have a high degree of uncertainty because differences in local geology and tectonic environment could significantly affect strong ground motion. If empirical predictions of strong ground motions for Utah earthquakes are ever to be developed with data from Utah, the number of accelerograph sites must be significantly increased.

- *Lack of free-field sites*. A number of the existing strong motion instruments in Utah are located in large buildings (at least 8 of the 25 sites), and therefore do not qualify as free-field sites. Strong motion records from large buildings on unconsolidated sediments may not accurately reflect the motion of the ground because of the distortion caused by the motion of the building and the interaction between the foundation and the surrounding sediments.
- *Uncertainty about ground motion amplification by sedimentary basins*. There is a major controversy over the extent to which the unconsolidated sands, silts, clays, and gravels that underlie most of the urban areas of Utah amplify ground motions during moderate and large earthquakes. Measurements by the U.S. Geological Survey of weak ground motions from nuclear explosions in Nevada have shown amplification of spectral velocities by as much as a factor of 10 to 15 in certain frequency bands at sites underlain by thick (450 to 750 m) unconsolidated deposits relative to sites underlain by bedrock. However, both the physical interpretation of these measurements and their relevance to the prediction of strong ground motions from nearby earthquakes are the subject of ongoing debate. A good set of strong motion records from a Utah earthquake recorded at sites located on both bedrock and on unconsolidated deposits would do much to settle this controversy.
- *No Federal plans for more strong-motion instrumentation*. The Federal government has no immediate or long-term plans for increasing the number of strong motion instruments in Utah. If the number of strong motion instruments in Utah is to be increased, the State must take the initiative.
- *Lack of instrumentation in buildings*. Although the State of Utah adopted the Uniform Building Code for statewide use in 1988, it did not adopt the appendix to the code that requires installation of accelerographs in high rise buildings located in seismic zones 3 and 4 (Appendix B-2). (This appendix is, however, included in the building code requirements in the unincorporated areas of Salt Lake County and possibly in other areas.) The purpose of these instruments is to provide records of the building motion during potentially damaging earthquakes so that a more rapid and accurate evaluation of the post-earthquake safety of

these buildings can be made. Note that most of the population of Utah lives in areas that are currently designated zone 3.

Specific Goals

- To obtain data from future large, potentially damaging earthquakes (M $\geq$5.5) in Utah relating to: (1) ground shaking near large, normal-faulting earthquakes, (2) the dependence of strong ground shaking on the distance to the fault, (3) the dependence of strong ground shaking on the geology underlying the site, and (4) threshold conditions for liquefaction of soils during strong ground shaking.
- To collect engineering data on the performance of structures in Utah during earthquakes. Such data would aid in the long-term improvement of building codes and practices both in Utah and elsewhere.
- To obtain records of the motions of high rise buildings and critical facilities during potentially damaging earthquakes that will help engineers and building officials determine the safety of these buildings following the earthquake.

Instrumentation Plan

Note: This section has undergone extensive revision to incorporate the suggestions and recommendations made by the Utah Policy Panel on Earthquake Instrumentation. The basic elements of the plan described here follow the recommendations of that panel. Some details have been added by the authors to complete the provisional plan envisioned by the panel. It should be emphasized that the policy panel specifically recommended the $1.6 million capital expenditure for strong motion instrumentation, and intended that an advisory panel eventually help to determine the final details of any strong motion program in Utah that might result from this initiative.

The Utah Policy Panel on Earthquake Instrumentation has recommended that a strong motion instrumentation program be established for the state of Utah. The program includes five key elements: (1) a volunteer advisory panel to provide technical advice and guidance for the program, (2) operation of the program by the Utah Geological and Mineral Survey, (3) one-time capital funds of $1.6 million to purchase and install instruments, (4) ongoing funding to support instrument maintenance, collection and analysis of data, and, if possible, procurement of additional instruments, and (5) supplemental funds from private sources and federal agencies for purchase of additional instruments.

Volunteer Advisory Panel

The volunteer advisory panel should have a balanced membership of 8 to 15 technically qualified seismologists, engineering geologists, structural and geotechnical engineers, building officials, and emergency planners. The main responsibility of the panel would be to provide the staff of the strong motion program with guidance and advice on how to best attain the goals of the program. Additionally, the panel would provide a forum for those who collect, process, and use data on earthquake ground motions, including researchers, engineers, and government officials. This will help to ensure a coordinated effort to mitigate the ground shaking hazards caused by earthquakes in Utah.

Program Operation

Collection of strong motion data from earthquakes requires a long-term commitment because opportunities to 'capture' strong ground shaking from earthquakes are relatively rare. For this reason, the policy panel recommended that Utah's strong motion instrumentation program be run by a state agency such as the Utah Geological and Mineral Survey (UGMS) rather than by an academic institution. A strong motion program would fit in well with the mission of the UGMS, which includes identifying and characterizing geologic hazards within the state and collecting and providing geologic information. Successful use of the data to improve the earthquake resistance of structures will require close cooperation between the strong motion program, the seismology program at the University of Utah, local and state government officials, and the local engineering community. We believe that the UGMS would be effective in fostering such cooperation.

The minimum staff needed to establish a strong motion instrumentation program for Utah would consist of an engineering seismologist, a geologist, one or two electronics technicians, and office support personnel. The engineering seismologist would direct the program, analyze data, and conduct research related to the program goals. The geologist would assist in identifying active faults to be instrumented, conduct geologic investigations of potential accelerograph sites, and obtain permission to install instruments from land and building owners. The technicians would install and maintain instruments. Once the initial 110 instruments had been installed, the geologist could assist with data analysis and dissemination and also perform other duties.

According to Genevieve Atwood, Director of the UGMS, the agency has two existing employees who would be available to assist in the operation of a strong motion instrumentation program: one full-time geologist and one electronics technician who could help install and maintain instruments on a half-time basis. At least two additional staff members, an engineering seismologist and an electronics technician, would need to be hired. In order to facilitate communication between the strong motion instrumentation program at the UGMS and the departments of Geology and Geophysics and Civil Engineering at the University of Utah, these departments should be encouraged to appoint the director of the strong motion instrumentation program to adjunct faculty positions.

Purchase and Installation of Instruments

The policy panel proposed that one-time capital funds be used to purchase strong motion accelerographs for Utah and pay for their installation. Because the first and most important goal of the program is to obtain quantitative data on strong ground shaking, the emphasis of the program, at least initially, should be on instrumentation of free-field sites. The policy panel recommended that initially at least 100 free-field sites and 8 structures be instrumented in Utah. In addition, they recommended the installation of at least one specialized array to study liquefaction, which would include instruments to measure pore fluid pressures (piezometers). In order to accomplish this task in a timely manner with the minimal permanent staff described above, it will be necessary either to hire temporary help or else to contract out much of the installation work.

Details of the program such as the types of instruments to be installed and their locations can be decided upon later with the help of the advisory panel. However, some consideration of these issues is necessary in order to determine the number of instruments required and their cost.

What types of instruments should be installed? Most accelerographs that are being installed today record data either in analog form on film or in digital form in solid state memory. With a high accuracy internal clock or radio time code receiver, the cost of an analog instrument is about $4700 and the cost of a digital instrument is about $6700. The advantages of a digital instrument over an analog instrument are: (1) the initial part of the signal can be recorded, (2) digital recording eliminates the loss of accuracy and bandwidth that occurs when an analog record is digitized for analysis, and (3) digital data can be analyzed immediately after retrieval whereas film data must be developed and digitized. The disadvantages of the digital instruments are the extra cost and the fact that they do not have the proven reliability of the older analog instruments. In the opinion of the authors and some of the members of the policy panel, the advantages of the digital instruments outweigh the disadvantages.

A standard accelerograph records ground acceleration from one vertical-component sensor and two horizontal-component sensors located within the same package as the recorder. Buildings are usually instrumented with a central recording device that records 9 to 12 channels of data from sensors located throughout the building. The cost of a 9-channel digital accelerograph system for a building, including cabling, is approximately $25,000.

Where should the free-field instruments be installed? For both scientific and engineering purposes, the most important data to capture with the strong motion accelerographs are the free-field ground motions from the next large ($M \geq 6.0$), surface-faulting earthquake in Utah. Thus, as a preliminary plan, we suggest installing accelerographs near each fault or fault segment in Utah that is likely to generate a surface-rupturing earthquake. In our judgment, these faults include all of those that have moved during the last 30,000 years and have average recurrence intervals that are less than 5,000 years or slip rates that are 0.3 mm/yr or greater. Based on a preliminary compilation of data on Quaternary faults in Utah by Suzanne Hecker of the Utah Geological and Mineral Survey, there are 15 faults and fault segments that are known or suspected to fall into this category (Figure B-1, Table B-1). These include six segments of the Wasatch fault and nine other miscellaneous faults and fault segments. It is important to keep in mind that information on slip rates, recurrence intervals, and timing of the most recent surface rupture is available for very few faults besides the Wasatch fault. Hence, Table B-1 may not include all of the faults in Utah that meet the criteria stated above.

It is worthwhile to note that moderate but potentially damaging earthquakes of up to M_L 6.0 to 6.5 could probably occur virtually anywhere in Utah on buried faults with no clear surface expression. Although these moderate earthquakes appear to be the most important source of seismic hazard at most localities over the short term, it is not possible at the present time to predict their locations in advance and it is therefore difficult to install strong motion instruments to record them in the near-field. The distribution of the faults that we have recommended for strong motion instrumentation covers most of the heavily populated areas of Utah, so any moderate earthquake that occurs close enough to a major city to cause damage would probably be recorded on at least some instruments in the damaged area. To increase the chances of recording strong motion data from a moderate earthquake in Utah, we recommend that strong motion accelerographs be installed at the locations of the ten broadband digital stations proposed under Element A of this instrumentation proposal. These proposed stations are well distributed throughout the main part of the Intermountain Seismic Belt, although the station spacing of 60 to 160 km is rather large. Colocation of strong motion accelerographs with the ten broadband digital stations will allow the application

Table B-1. Faults Recommended for Strong Motion Instrumentation (In order of priority)

Map Code	Fault Name	Fault Length (km)	Number of Existing Instruments (Excluding Seismoscopes)[a]	Number of New Instruments proposed[b]
	Wasatch fault:[c]			
BC	Brigham City segment	40	1[d]	3+4=7
W	Weber segment	61	1[d]	4+4=8
SLC	Salt Lake City segment	46	10[e]	3+4=7
P	Provo segment	69.5	1[d]	4+4=8
N	Nephi segment	42.5	1[d]	3+4=7
L	Levan segment	30.0	0	3+4=7
	Other faults:[f]			
HV	Hansel Valley West	14	0	2+3=5
	Hansel Valley East	26	0	3+1=4
BR	Bear River	10	0	2+4=6
EGSL	East Great Salt Lake (North segment)	45	0	3+3=6
EGSL	East Great Salt Lake (South segment)	50	0	4+0=4
EC	East Cache (Central segment)	18	1[d]	2+4=6
A	Annabella	6	1[d]	2+4=6
NO	Northern Oquirrh Mts.	26	0	3+4=7
WV	West Valley	18	10[e]	2+0=2
				90

[a] Based on a preliminary compilation of strong motion instrument sites in Utah by William F. Case, Utah Geological and Mineral Survey

[b] Number of instruments along fault + number of instruments in cross array = total number proposed

[c] Segment boundaries and fault lengths taken from Segmentation models and Holocene movement history of the Wasatch fault zone, Utah, by M.N. Machette et al., U.S. Geol. Surv. Open-File Rept., in press

[d] Not a free-field site

[e] Some of these are not free-field sites

[f] Fault lengths measured from the Quaternary Tectonic Map of Utah, by S. Hecker (in preparation)

of powerful new techniques for correcting seismograms of large earthquakes for wave propagation effects using seismograms of small earthquakes recorded at the same site.

The portable array proposed under Element C of this instrumentation proposal will have force balance accelerometers for recording strong motion data. The availability of this array will allow temporary installation of digital strong motion accelerographs in response to increased earthquake activity anywhere in the state.

How many free-field instruments are needed? In order to gauge the number of free-field instruments required to meet the goals stated above, it is necessary to consider the data set that one would need to collect from each large surface-faulting earthquake that occurs. This data set would need to include recordings from at least two or three locations along the surface rupture to provide data on strong ground shaking near the fault and its variablility. It would also need to include recordings at various distances from the surface rupture so that the dependence of strong ground shaking on distance could be determined. This distance dependence is not expected to be the same on both sides of the fault because the fault rupture for a large, normal-faulting earthquake is usually not vertical but instead dips beneath the valley adjacent to the fault. Finally, recordings are needed from sites located both on bedrock and on unconsolidated deposits of various thicknesses so that the effect of site geology on strong ground shaking can be evaluated.

For reasons discussed above, we recommend colocating ten of the strong motion accelerographs with the proposed broadband digital stations. Table B-1 presents a first cut plan for the distribution of the remaining 90 free-field accelerographs. We have chosen to put two to four instruments along each of the targeted fault segments, depending on its length. These instruments would be spaced 10 to 15 km apart. Along most of the faults, four additional instruments would be placed in a linear array perpendicular to the surface trace of the fault. Three of the instruments in the linear array would be located on unconsolidated deposits in the valley adjacent to the fault at distances of 5, 10 and 20 km from the fault trace. The fourth instrument would be located on bedrock on the other side of the fault at a distance of approximately 10 km from the fault trace. Given this distribution of instruments, a large earthquake along any of the targeted faults would provide some useful data on all of the important issues regarding strong ground motion from earthquakes in Utah.

Note that the number of free-field instruments recommended for each fault segment (generally six to eight) is by no means excessive. A much larger number of instruments would be needed to provide a truly definitive data set from a future earthquake on any of these faults. More accelerographs could be installed along some of the fault segments if the number of fault segments to be instrumented was reduced. However, given the present state of knowledge about the behavior of Utah's faults, the location of the next large, surface-faulting earthquake in the state is very uncertain. Therefore, it appears prudent to instrument many fault segments in order to maximize the chances of collecting near-field data from the next large earthquake.

Operating Funds

Operation of a strong motion instrumentation program requires long-term, stable funding. Instruments must be visited twice a year for maintenance, and additional visits are required to collect data when instruments are triggered by earthquakes. The importance of regular maintenance and testing should not be underestimated; during the 1975 Pocatello Valley earthquake, the accelerograph located in Logan was triggered but the instrument malfunctioned and valuable data was irretrievably lost.

To ensure stability for Utah's strong motion program, the Director of the UGMS has recommended that ongoing funding of at least $120,000 per year be provided for staff and operating costs. This would include salaries for the engineering seismologist and one electronics technician; it would not include the salaries of the geologist, another technician, and office support personnel. These additional costs would need to be considered if the strong motion program were not located at the UGMS. The success and stability of the strong motion program in California is partly due to a steady source of funding from a mil levy on construction costs (7¢ or 15¢ per $1000 of construction costs, depending on the type of construction). The Utah Policy Panel on Earthquake Instrumentation recommended this type of funding source because it has the advantage of automatically adjusting to inflation and economic development.

Supplemental Funds

The policy panel advised that the initial deployment of 108 strong motion instruments was not the *total* number of instruments needed in Utah, but rather the *minimum* number needed for a reasonable strong motion network. Therefore, it would be the responsibility of the director of the strong motion program to seek additional funds from federal agencies and private industry for expansion of the strong motion network to an optimal level. The policy panel concurred that a state-established strong motion program with additional specific instrumentation needs could probably obtain external funding from such sources as the National Science Foundation and private companies interested in purchasing instruments to be installed on their property. Another possible avenue of external support discussed by the panel was a cooperative arrangement with the U.S. Geological Survey whereby the Survey would provide one or two additional engineering seismologists as visiting scientists.

The buildings to be instrumented under the strong motion program would be those having specific design and/or construction characteristics whose seismic performance needs to be evaluated. The panel envisioned that the purchase and installation of accelerographs in high rise buildings and critical facilities for the purposes of public safety would be done by the owners, under the general supervision of local building officials. This presupposes that either local governments or the state could be persuaded to adopt the appendix of the Uniform Building Code that requires accelerographs in high rise buildings (Appendix B-2 of this report), or some modified version thereof. Such legislation could only be passed with strong support and leadership from the local structural engineering community.

Justification for Instrumentation Plan

- If appropriate instrumentation is not in place to record strong ground shaking from the next large earthquake in Utah, valuable scientific and engineering data will be lost forever.
- There is considerable controversy regarding the adequacy of current seismic design criteria for buildings in Utah. We need hard data on strong ground motion from Utah earthquakes to help put an end to this controversy. If current design practises are inadequate, we are subjecting ourselves to unnecessary risk. On the other hand, overdesigning of structures adds unnecessary costs to construction.
- The probability of a large earthquake on the Wasatch fault during the next 50 years has been estimated by D.M. Perkins of the U.S. Geological Survey to be between 4 and 20%. The probability of a major, damaging earthquake in Utah is higher than this because of the possibility that such earthquakes could occur on other faults as well.
- The International Workshop on Strong-Motion Earthquake Instrumentation Arrays in 1978 included Salt Lake City, Utah, as one of only three places in the United States and 28 places in the entire world on its list of recommended locations for strong motion arrays.
- The cost of the strong motion program proposed above is small compared to the $4.5 to $5.5 billion of building damage that is expected to occur in a magnitude 7.5 earthquake on the central part of the Wasatch fault.

- Depending on the timing of future moderate-to-large earthquakes in Utah, the strong motion instrumentation program may not pay off in the short term, but future generations will unquestionably benefit.

Acknowledgments

In preparing this report, we have benefitted greatly from information and advice provided by A.F. Shakal of the California Division of Mines and Geology; C. Rojahn of the Applied Technology Council; J.H. Wiggins of Crisis Management Corporation; C.B. Crouse of Dames and Moore; R.D. Borcherdt, E. Athridge, and R. Maley of the U.S. Geological Survey; W.F. Case and S. Hecker of the Utah Geological and Mineral Survey; A. Viksne of the U.S. Bureau of Reclamation; W.J. Arabasz, E. McPherson, and S.J. Nava of the University of Utah; and M. Lund of Kinemetrics, Inc.

Cost Estimate

A. One-Time Costs

100 digital accelerographs with high accuracy clocks @ $6,700 each	$670,000
Materials for 100 instrument shelters @ $2,300 each	230,000
Installation of 100 free-field instruments (including pad and hut construction) @ $2,000 each	200,000
8 digital strong-motion accelerograph systems for buildings @ $25,000 each	200,000
Installation of 8 strong-motion accelerograph systems in buildings @ $25,000 each	200,000
Instrumentation for liquefaction array	60,000
2 portable PC-based systems for instrument testing and data retrieval @ $3500 each	7,000
PC-based system for data analysis, with software	13,000
Computer work station for data analysis and research	20,000
Total one-time costs	$1,600,000

B. Recurring Annual Costs

Maintenance (semiannual visits), data collection, and data processing	$120,000

Appendix B-1

Table 1: Location of strong-motion instrument sites; Map number keyed to figures 1 and 2.

Map No.	Strong-motion instrument sites in Utah (instruments: SMA-1, CRA-1, seismoscope; contact agency: I, II, III, see footnotes)	Latitude ddmmss	Longitude dddmmss
1	Logan; Utah State University Administration Building basement: SMA-1 (I).	414427	1114849
2	Hyrum Dam; SMA-1 on right abutment, CRA-1, 9-channel system in dam, (III).	413824	1115212
3	Brigham City; Fire Station, basement: SMA-1 (I).	413110	1120052
4	Ogden City; Fire Station #2, basement: seismoscope (II).	411344	1115648
5	Ogden City; Fire Station #1, storage shed: seismoscope (II).	411308	1115820
6	Ogden City; Weber State College: SMA-1 (I).	411140	1115622
7	East Canyon Dam; SMA-1's downstream, on center crest, and right crest (III).	405519	1113600
8	Flaming Gorge Dam; SMA-1's in upper and lower gallery of dam (III).	405454	10925[illegible]
9	Salt Lake City; NOAA Weather Service building, east airport: SMA-1, (I), (F).	404702	11157[illegible]8
10	Salt Lake City; UP & L building, Temple Sq. west, (40 North First West): SMA-1 (I), (F).	404614	1115341
11	Salt Lake City/County Building: two 12-channel CRA-1's (I), (F).	404534	1115310
12	Salt Lake City; V A Hospital Building #1; SMA-1 in basement and on 9th. floor (I).	404527	1115023
13	Salt Lake City; Mountain Fuel Sunnyside Training Center garage: SMA-1, (I), (F).	404437	1114849
14	Salt Lake City; Salt Lake Junction, A T & T Communications garage, bedrock site (3100 Kennedy Dr.):SMA-1, seismoscope, (I,II), (F).	404500	1114829
15	Salt Lake City; Liberty Park Horseshoe storage building: SMA-1, (I), (F).	404449	1115217
16	Salt Lake City; Sugar House Fire Station #3, Fairmont City Park (1085 Simpson Ave) solvent storage room: seismoscope (II), (F).	404320	1115135
17	South Salt Lake; Fire Station #1 (90 East Oakland Ave): seismoscope (II), (F).	404253	1115316
18	Salt Lake City; Roosevelt Elementary School shed (800 East Springview Dr.): SMA-1, seismoscope, (I, II), (F).	404103	1115157
19	Salt Lake City; Eastwood Elementary School (3305 Wasatch Blvd.): SMA-1, (I).	404059	1114734
20	Salt Lake City; Olympus Junior High School (2217 East 4800 South): seismoscope (II), (F).	404009	1114042
21	Salt Lake City; Cottonwood Elementary School storage building* (5205 Holladay Blvd.): SMA-1, (I), (*soon to be moved).	403922	1114854

Table 1: Location of strong-motion instrument sites; Map number keyed to figures 1 and 2 (continued).

Map No.	Strong-motion instrument sites in Utah (instruments: SMA-1, CRA-1, seismoscope; contact agency: I, II, III, see footnotes)	Latitude ddmmss	Longitude dddmmss
22	Kearns, Salt Lake County; Sheriff's posse building: seismoscope (II), (F).	403911	1115947
23	Jordanelle Dam site: upstream from right abutment SMA-1 (III).	403542	1112525
24	Upper Stillwater dam; field station SMA-1 (III).	403332	1104157
25	Deer Creek Dam; SMA-1 on toe and left abutment (III).	402400	1113148
26	Provo; Utah State Hospital: SMA-1 (I).	401401	1113755
27	Soldier Creek Dam; SMA-1 on left abutment, slope, and crest (III).	400813	1110134
28	Nephi; Juab High School (555 East 800 North): SMA-1 (I).	394239	1115005
29	Joes Valley dam; SMA-1 on crest, midslope, and toe (III).	391724	1111612
30	Richfield; Utah Dept. of Highways garage (100 West 708 South): SMA-1 (I).	384529	1120509
31	Cedar City; Southern Utah State College Library, seismic vault: SMA-1 (I).	374032	1130406

SMA-1 and CRA-1 are manufactured by KINEMATICS, Pasadena, California)

I. United States Geological Survey, Menlo Park, California: Arnold Acosta (213-297-1672), Richard Maley (415-329-5670).

II. United States Geological Survey, Denver, Colorado: Dave Carver (303-236-1618), Ken King (303-236-1591).

III. Bureau of Reclamation, Denver: Andy Viksne (303-236-4196), Bureau of Reclamation, Salt Lake City: Dan Grundvig, (801-524-4161).

Appendix B-2

Division II
EARTHQUAKE RECORDING INSTRUMENTATION

General

Sec. 2326. In Seismic Zones No. 3 and No. 4 every building over six stories in height with an aggregate floor area of 60,000 square feet or more, and every building over 10 stories in height regardless of floor area, shall be provided with not less than three approved recording accelerographs.

Location

Sec. 2327. The instruments shall be located in the basement, midportion, and near the top of the building. Each instrument shall be located so that access is maintained at all times and is unobstructed by room contents. A sign stating "Maintain Clear Access to This Instrument" shall be posted in a conspicuous location.

Maintenance

Sec. 2328. Maintenance and service of the instruments shall be provided by the owner of the building subject to the approval of the building official. Data produced by the instruments shall be made available to the building official upon his request.

Instrumentation of Existing Buildings

Sec. 2329. All owners of existing structures selected by the jurisdiction authorities shall provide accessible space for the installation of appropriate earthquake-recording instruments. Location of said instruments shall be determined by the jurisdiction authorities. The jurisdiction authorities shall make arrangements to provide, maintain and service the instruments. Data shall be the property of the jurisdiction, but copies of individual records shall be made available to the public upon request and the payment of an appropriate fee.

SEISMIC ZONE TABULATION
For Areas Outside the United States

Location	Seismic Zone
ASIA	
Turkey	
Ankara	2
Karamursel	3
ATLANTIC OCEAN AREA	
Azores	2
Bermuda	1
CARIBBEAN SEA	
Bahama Islands	1
Canal Zone	2
Leeward Islands	3
Puerto Rico	3
Trinidad Island	2
NORTH AMERICA	
Greenland	1
Iceland	
Keflavik	3

Location	Seismic Zone
PACIFIC OCEAN AREA	
Caroline Island	
Koror, Paulau	2
Ponape	0
Johnston Island	1
Kwajalein	1
Mariana Islands	
Guam	3
Saipan	3
Tinian	3
Marcus Island	1
Okinawa	3
Philippine Islands	3
Samoa Islands	3
Wake Island	0

ELEMENT C

Portable Seismographs for Strategic Data Collection

by W.J. Arabasz, R.B. Smith, and E. McPherson

When you are out to describe the truth,
leave elegance to the tailor.

Albert Einstein

THE AUTHORS

All are affiliated with the University of Utah Seismograph Stations—and all have extensive experience with portable seismographs and their use in major field experiments. Further, all have been directly involved since 1983 in a national program to develop modern portable digital seismographs for observational seismology.

Statement of Problem

For earthquake hazard reduction, scientists and engineers require detailed, high-quality seismographic data for characterizing the source mechanics, propagation effects, and the resulting ground motions of earthquakes.

Utah's regional seismic network serves the purpose of continuous temporal recording on a regionwide basis. For individual earthquake sources, however, the distribution and density of the network stations (even after proposed upgrading and network expansion) won't generally provide critically-needed recordings at very close distances—or recordings that may be needed in other spatial configurations such as along linear profiles.

Supplementing a fixed regional seismic network with versatile portable seismographs is a fundamental data-collection strategy of earthquake seismology. Existing portable seismographs in Utah, however, are worn, outdated, and inadequate. They consist of 10 analog (MEQ-800) smoked-paper-recording instruments acquired about 1970 and three outmoded digital seismographs home-fabricated in the early 1980's.

(Note: The number of analog portable seismographs we have is actually five. Five of the MEQ-800's belong to Southern Methodist University; they were acquired for collaborative research with the University of Utah, are on loan to us, and have to be returned eventually.)

General Goals

The basic reason for having and using modern portable digital seismographs in Utah is to enable the strategic collection of high-quality seismographic data—data that can't simply be collected with the fixed regional network because of the inadequate distribution and wide spacing of its stations. The most important *What?* is high-quality data. By this, we mean three-component broadband recordings of undistorted seismic waveforms at many stations, with precise timing, and including recordings at map distances within a few to several kilometers of earthquake sources.

(For a regional network, the station density needed to acquire the high-quality data described above would involve literally 100's to 1000's of telemetered stations, clearly beyond the scope of a fixed network.)

Where? and *When?* are linked. Earthquakes originate in discrete seismic source zones that can be monitored randomly in time with arrays of portable seismographs if the sources generate sufficient "background" seismicity of small to moderate size—say, less than magnitude 4.0. When any source zone produces a mainshock-aftershock sequence, it immediately becomes an important "target" for portable-array recording because it produces lots of earthquakes in a short amount of time. The seismic source zones in Utah that are important targets for study include:

- segments of the Wasatch fault and other identifiable faults having evidence of late Quaternary (<500,000 yr) displacement—and hence the potential for producing large surface-faulting earthquakes;
- source zones that have produced historical shocks of magnitude 5 and greater; and
- any activated source zone that produces a shock of magnitude 4 or greater (see Attachment No. 4, p. 23, regarding the importance in Utah of buried sources that produce moderate-size earthquakes not constrained to occur on mapped faults).

The *Why?* of using portable seismographs brings us to the heart of the matter. Ultimately, any prospect for earthquake prediction rests on understanding the physics of earthquake generation and the detailed behavior of individual source zones, both of which demand the systematic collection of the high-quality data we're describing. The more immediate practical goals are so-called earthquake prognostics—hazard assessment, risk evaluation, and loss reduction.

Rigorous estimations of earthquake hazard (and of corresponding "risk" of social or economic consequences) involve carefully prescribed quantitative models of the space, time, and size distribution of earthquakes giving rise to that hazard, together with models of ground-motion attenuation with distance. Figure C-1 outlines the detailed information from observational seismology upon which a reliable earthquake hazard analysis depends. In Utah, much of that detailed information has come, and will continue to come, from portable-array recordings. Each of the key pieces of seismological information in Figure C-1 is an important goal of this instrumentation element.

In particular, portable-array data will be critical for:

- the correlation of seismicity with known or suspected geological structure (dependent on refined hypocentral resolution, improved models of crustal structure, and single-event focal mechanisms);
- advances in understanding the source mechanics of normal-faulting earthquakes (dependent on reliable determinations of earthquake source parameters);
- the modeling and estimation of ground motions for engineering applications (dependent on analyses of source, propagation, and site effects), especially for problems relating to the effects of deep alluvial valleys along the densely urbanized Wasatch Front.

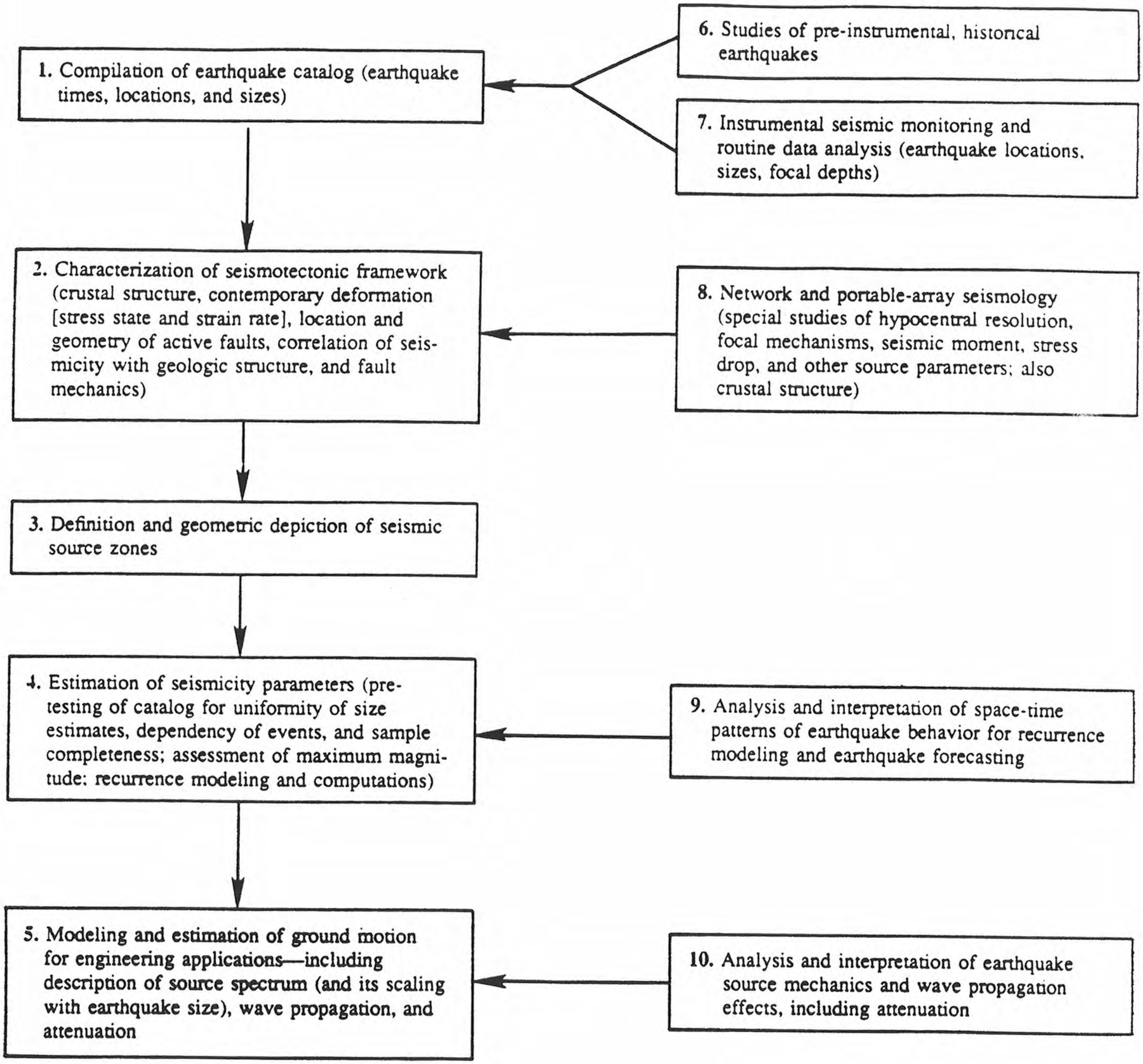


Figure C-1

Flowchart outlining steps in a formalized earthquake hazard analysis (left column) and interrelated aspects of observational seismology (right column). (Taken from Arabasz and others, in press; see Attachment No. 4.)

As a routine part of our proposed field recording with portable seismographs, our planned use of force-balance accelerometers will allow the recording of free-field ground motions, providing basic information on attenuation and local site response for earthquake engineering.

We emphasize that much remains to be learned about the mechanics of large normal faulting earthquakes—the main threat in Utah. Most large destructive earthquakes for which there is good information are from plate boundaries characterized by strike-slip and thrust faulting events.

Background on State-of-the-Art Portable Digital Seismographs

During the past 6 years, the U.S. seismological community has made concerted efforts to develop a new generation of portable digital seismographs for versatile applications in both earthquake seismology and lithospheric seismology. The process began in 1983 with a national workshop organized by two of us (RBS and WJA) on "Guidelines for Instrumentation Design in Support of a Proposed Lithospheric Seismology Program." Subsequent developments leading to the Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL) as part of the IRIS university consortium for seismology are summarized in a review paper by S.W. Smith (1987), included here as Appendix C-1.

(Note: In perusing Appendix C, the reader should not be misled by the lead statement in the abstract: "IRIS is a university consortium organized to provide modernized seismographic networks and data distribution facilities for the university research community and funded by the National Science Foundation (NSF)." The "networks" that are referred to simply relate to an optimistic program goal of eventually having as many as 1000 new portable digital seismographs acquired, maintained, and deployed under the IRIS/PASSCAL program for special cooperative field experiments requiring large numbers of instruments. Federal appropriations have fallen far short of the program goals, and even when the instruments do become available, they will not solve the need in Utah to have at least some small number of portable digital seismographs continually available for both ongoing and emergency use.)

The important point for this position paper is that, under the PASSCAL program, a state-of-the-art portable digital seismograph system has been developed —based on consensus specifications made by the U.S. seismological community and intended to be a national standard useable for at least the next decade. A description of the PASSCAL portable digital seismograph is given in Appendix C-2.

We've received a one-time award from internal funds of the University of Utah, allowing us to acquire <u>one</u> of the PASSCAL portable digital seismographs (Reftek Model 72-02A) without new sensors. The instrument has been ordered and is scheduled for delivery sometime during the next few months. Our intent in acquiring the seismograph is to use it for educational and training purposes and as a basis for planning the upgrading of our outmoded portable instrumentation.

Instrumentation Plan for Portable Seismographs

We've made a deliberate decision at the outset to propose an instrumentation plan that we consider *conservatively minimal*. We've done this for two reasons:

- New portable digital seismographs are crucial for our basic and applied research. Given the total dollar amount for the combined instrumentation needs of the various elements, we don't want to jeopardize any chance for successfully funding portable seismographic instrumentation.

- Any need for a large number (say tens or more) of portable seismographs for special short-term field experiments could be handled by submitting a proposal for short-term use of the IRIS/PASSCAL instruments. We feel that 10 new portable digital seismographs would be adequate for most of our field-recording needs and would be manageable without requiring additional personnel for maintenance and deployment.

Specific Goals for a Minimal Program Include:

- An ability to deploy several portable seismographs *rapidly* (within a few hours of the occurrence of a significant local earthquake).

- A capability to record three-component digital data simultaneously at several stations close to an earthquake source—including some *broadband onscale recording* crucial for local earthquakes (e.g., aftershocks) that may exceed magnitude 4.0 to 4.5.

- Versatility in data collection and recording modes—including an ability to transmit some subset of data channels to our central recording lab via our state microwave telemetry network.

- A capability to collect routinely—virtually as part of all temporary field recording—ground-motion data supplementary to the strong-motion program.

Our instrumentation plan for portable digital seismographs has 7 basic parts:

1. Acquire 5 lower-cost portable digital seismographs, at about 40 percent of the cost of PASSCAL seismographs, for operation with standard three-component 2-Hz velocity sensors.

2. Acquire 4 PASSCAL portable digital seismographs (in addition to one that we've already ordered to make a set of 5), together with 5 sets of dual sensors consisting of three-component 2-Hz velocity sensors <u>and</u> three-component force-balance accelerometers.

3. Acquire field computers needed for (a) downloading data from the digital recorders at field sites and (b) data processing/analysis away from our research lab during a field experiment.

4. Acquire trailer for field transportation and in-field use in connection with portable seismographs.

5. Refurbish 5 of the existing analog portable seismographs (MEQ-800's) that we currently have for continued use as part of a rapid-deployment strategy in aftershock situations.

6. Acquire accessory equipment essential for the effective field operation of portable seismographic instrumentation.

ESTIMATED ONE-TIME COSTS

A. Five Lower-Cost Portable Digital Seismographs

(5) Portable seismographs, EDA Model PRS4 (with at least 2 Mbyte extra memory) @ $6,000 ea	$ 30,000
(5) Three-component 2-Hz velocity sensors, Mark Products Model L22D-3DL (with cable and connectors) @ $ 1,550 ea	7,750
	$ 37,750

B. Five PASSCAL Portable Digital Seismographs

[Note: One recorder, funded by a one-time special research award from the University of Utah has already been ordered.]

(4) Portable seismographs, Reftek Model 72-02A PASSCAL recorder (with battery pack, Omega receiver, and clock) @ $ 15,600 ea	62,400
(5) Three-component force balance accelerometers, Kinemetrics Model FBA-23 (with cable and connectors) @ $ 2,800 ea	14,000
(5) Three-component 2-Hz velocity sensors, Mark Products Model 122D-3DL (with cable and connectors) @ $ 1,550 ea	7,750
(5) 9-Watt solar panels @ $ 130 ea	650
	$ 84,800

C. Field Computers

(1) SUN Sparc workstation with 200 Mbyte disk and monochrome monitor	12,000
(1) Laptop computer for routine data retrieval (downloading of digital seismographs) at field sites	5,200
	$ 17,200

D. Trailer for Field Transportation of Portable Seismographs

(1) Trailer, Wells Cargo Model EW1625 (with shelving, 2.5 KW portable generator, and electrical cables and hardware)	**$ 7,200**

E. Parts for Refurbishing 5 Existing Analog Portable Seismographs	
(5) Sets of translation motors, rotation motors, and other parts requiring refurbishing @ $ 500/instrument	**$ 2,500**
F. Accessory Equipment and Supplies for Field Use of Portable Seismographs	
• Replacement batteries for 10 recorders (@ $ 125 ea) plus (5) battery chargers (@ $ 175 ea)	2,125
• (10) padded containers for field transportation of digital seismographs @ $190 ea	1,900
• Essential equipment for electronic testing and field repair, including oscilloscope ($3,200), voltmeter ($300), hand tools ($250), test cables ($200), and spare parts ($400)	4,350
• Essential supplies for routine field operations, including (10) tarpaulins (@ $35 ea), maps ($200), digging tools ($150), and misc. supplies (heavy-duty jack, first-aid kits, flashlights, coveralls, etc.) @ $750	1,450
	$ 9,825
TOTAL ONE-TIME COSTS	**$ 159,275**

ESTIMATE OF RECURRING COSTS

• Maintenance/repairs at 10 percent of capital costs for electronics	14,000
• Misc. supplies	3,000
• Vehicle usage for field operations	5,000
ESTIMATE OF TOTAL ANNUAL RECURRING COSTS	**$ 22,000**

TOTAL ESTIMATED COSTS $ 181,275

Justification of Instrumentation Plan

- We've persistently argued for, and demonstrated the justification of, portable array studies to supplement our regional seismic network. Our network's large station spacing and its limitations of dynamic range and bandwidth have been continual frustrations for obtaining good hypocentral resolution and for carrying out modern waveform studies. To emphasize the problem of hypocentral resolution, Attachment No. 4 (p. 19) points out that out of 6,416 earthquakes located by our network in the Wasatch Front area from late 1974 through 1986, only 485 (< 8%) have reliable focal-depth determinations.

- To illustrate the extensive use of portable seismographs made by University of Utah researchers, Figure C-2 shows the locations of 25 special earthquake field experiments carried out between 1970 and about 1982 chiefly using portable analog seismographs. Since 1982, seven aftershock studies have been carried out in Utah in response to earthquake mainshocks between magnitude 4.3 and 5.4 (e.g., Appendix C-3).

- Figure C-3 (taken from a recent M.S. thesis by J. Shemeta at the University of Utah) illustrates the contrast between hypocentral resolution achievable with portable digital recorders versus that achievable with standard analog recorders. Data acquired by portable digital seismographs from the Borah Peak, Idaho, earthquake sequence (used also for determining source parameters and for velocity inversion) are unequalled by any data available for the Utah region. Indeed, the Borah Peak data set drives our perception of the type of data needed in Utah.

- To date, most of what we've learned about the mechanics of normal faulting in Utah and the Intermountain seismic belt has come from research using portable seismographs. For example, Figure C-4 and C-5 (taken from Arabasz and Julander, 1986, *Geol. Soc. of America Special Paper 208)* illustrate the apparent influence of low-angle detachments on the distribution of background seismicity.

- Models from Smith and others (Figs. C-6 and C-7) for the nucleation of large normal-faulting earthquakes emphasize the requirements for high-quality seismographic data for effective surveillance of the Wasatch fault. The data are needed for the reliable determination of the subsurface geometry of faulting, source properties, and the modeling of ground-motion response of associated basins and mountain blocks.

- The lower-cost portable digital seismographs that we've selected are important both from the point of view of cost and speed of deployment. The latter demands that the seismographs (1) be compact and light, (2) require little or no set up programming in the field, (3) have an accurate, internal, pre-programmable time source, (4) use small, lightweight seismometers that can simply be set on the ground, and (5) have a very low power requirement so heavy or bulky power supplies are not required. The deluxe PASSCAL seismograph has many desirable features for multichannel field recording but is more cumbersome than the EDA's to deploy.

- Arguments for the value of the force-balance accelerometers and dual recording with velocity transducers to provide extended dynamic range have been developed at length in the position papers for Elements A and B. The broadband sensor and the increased dynamic range are important for local recordings of earthquakes of about magnitude 4 and greater.

- Our extensive experience with portable seismographs and field experiments tells us that the budget items for a trailer and accessory equipment are essential for effective data collection and for proper maintenance of the costly equipment. The field computers are unquestionably essential for the operation of digital seismographs.

LOCATIONS OF SPECIAL EARTHQUAKE FIELD EXPERIMENTS CARRIED OUT BY UNIVERSITY OF UTAH SEISMOLOGISTS

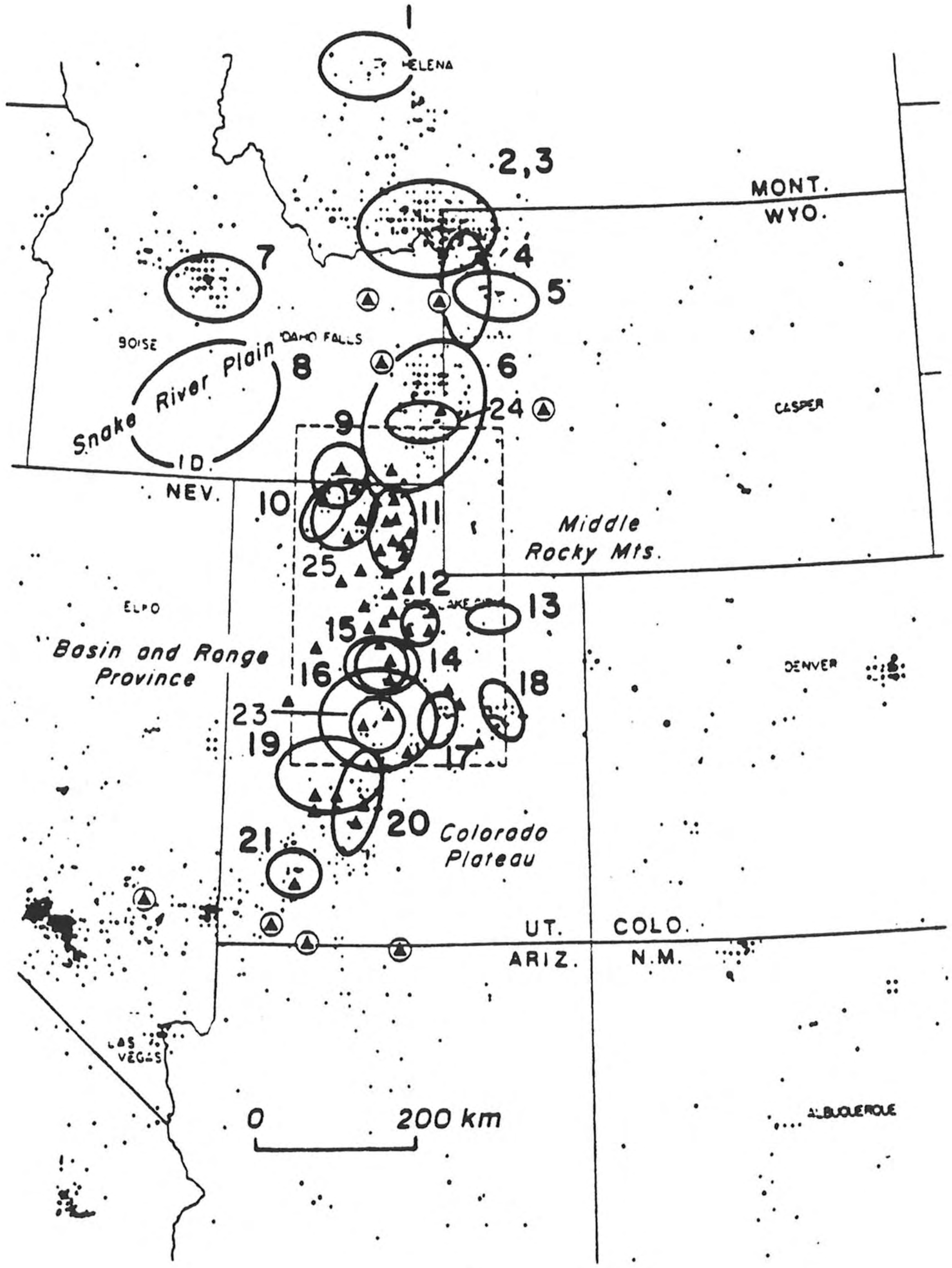


Figure C-2.

Schematic locations of 25 earthquake field experiments, including aftershock studies, carried out by University of Utah researchers between about 1970 and 1982.

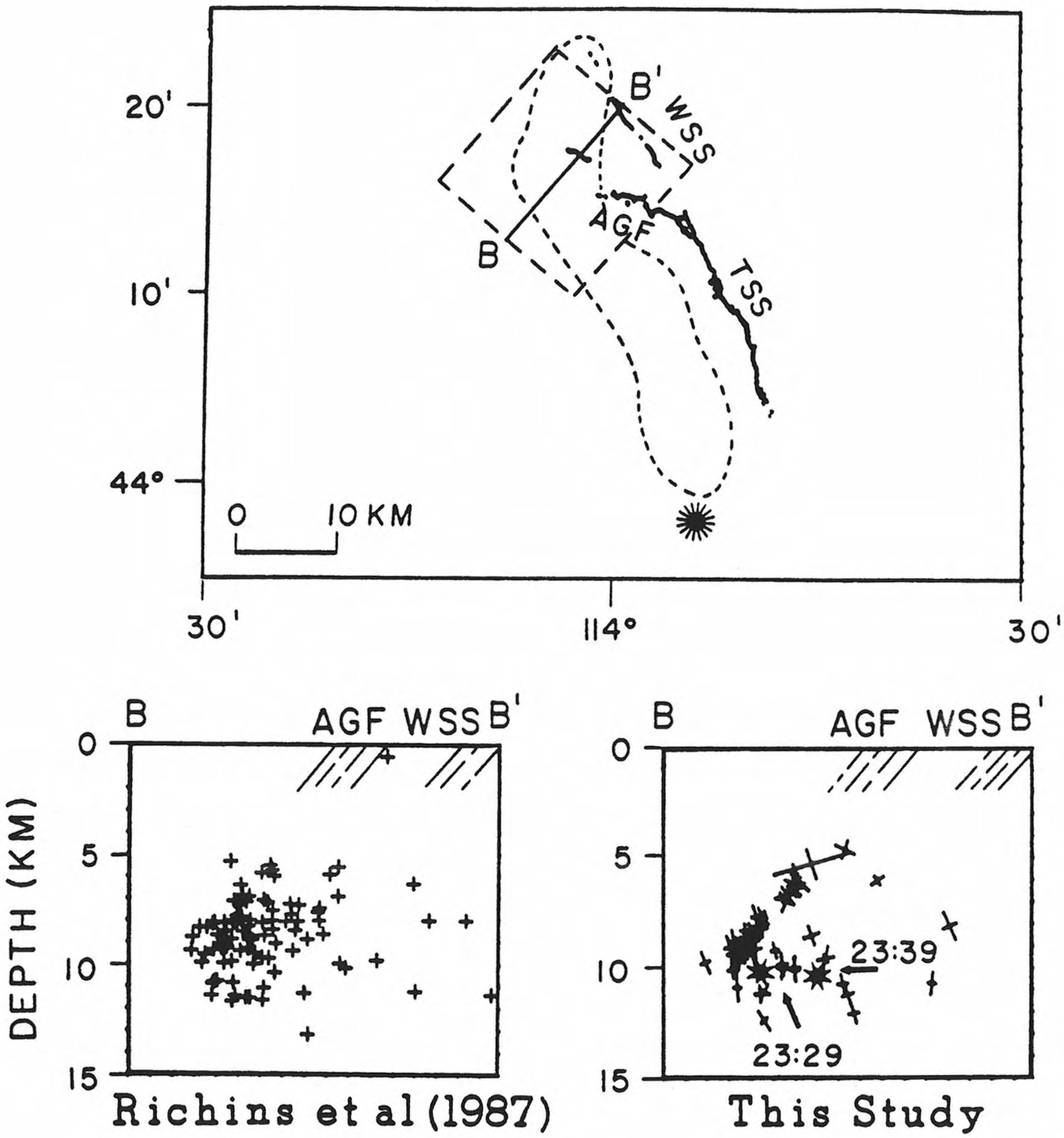


Figure C-3.

(from Shemeta, 1989) Vertical cross section along B-B', for aftershocks of the 1983 Borah Peak, Idaho earthquake. Upper plot shows the orientation of the cross section with respect to the surface rupture [bold solid line]. Dotted line encloses the aftershock distribution. The lower left plot shows hypocenters calculated using P-wave arrival time data from primarily analog instruments and the lower right plot shows hypocenters calculated using P- and S-wave arrival time data from 3-component digital instruments.

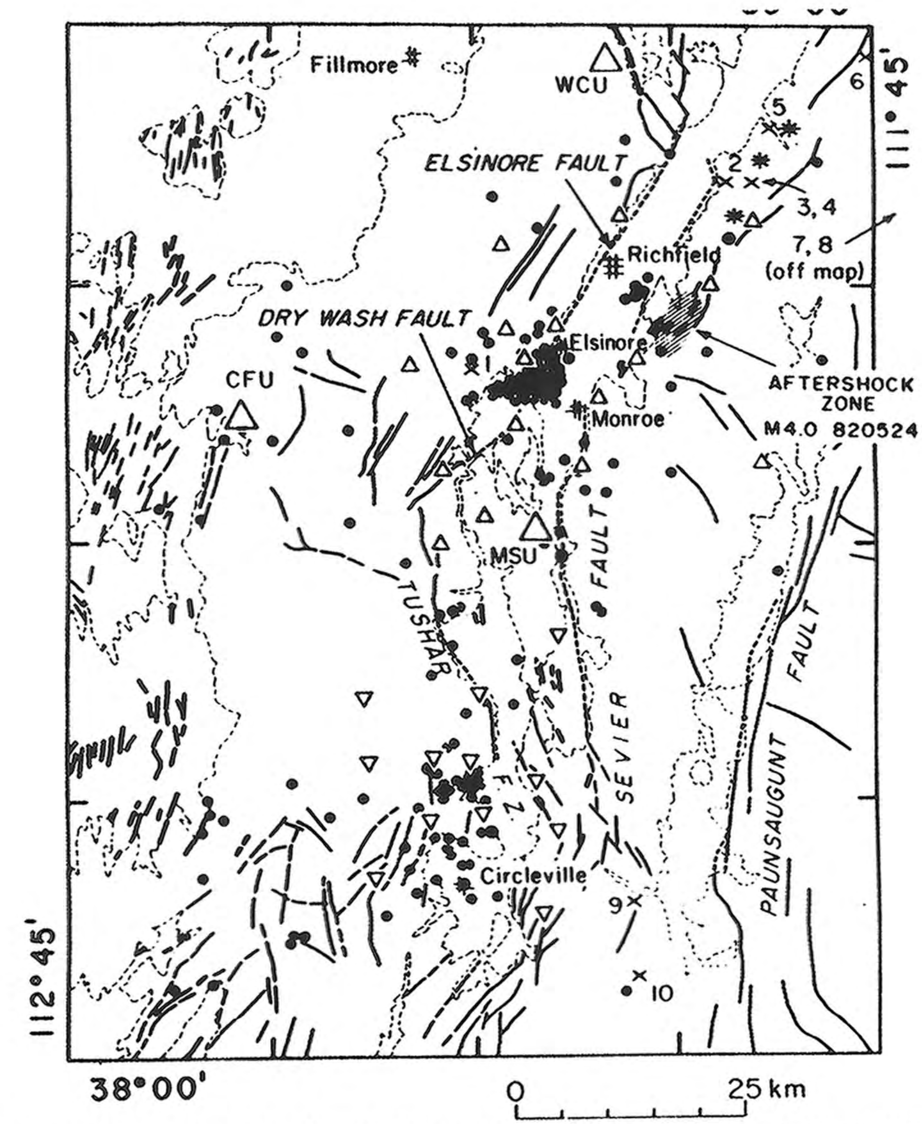


Figure 10. Summary map of earthquake field experiments in the Sevier Valley area during 1981 (1982 follow-up study within aftershock zone near Richfield). Base map as in Figure 2, but more detailed. Solid circles are epicenters (with mean epicentral precision <2 km); triangles, seismograph stations (larger ones, permanent stations; smaller ones, temporary—associated with two separate arrays represented by upright and inverted small triangles); X's and asterisks, sites of drill holes and quarry blasts, respectively, used for special investigation of upper-crustal structure. Cenozoic faulting shown by heavy lines—heaviest for late Quaternary fault scarps in unconsolidated alluvium (Anderson and Bucknam, 1979).

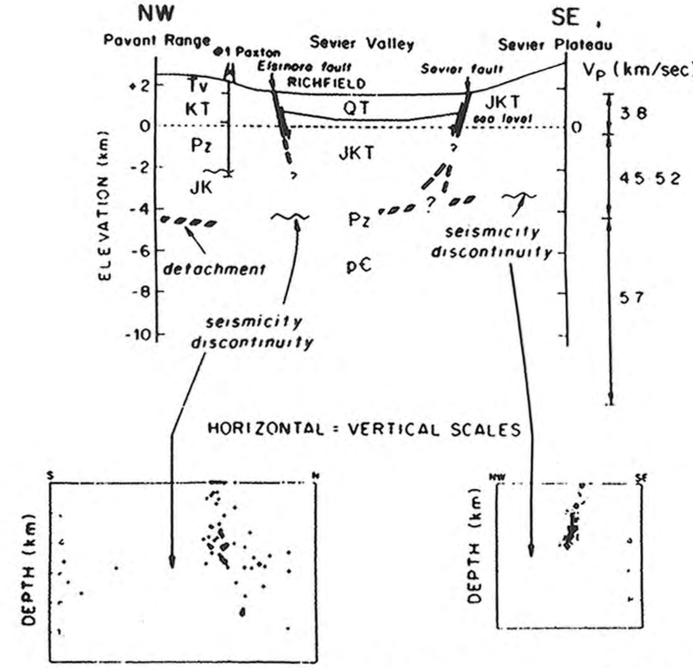


Figure 11 Schematic section across the Sevier Valley near Richfield, Utah, illustrating key results from local earthquake studies. Spatially discontinuous seismicity with depth appears to reflect local structural control by an inferred low-angle detachment (see text for discussion). Local P-wave velocity structures determined from nearby quarry blasts as refraction sources and by analysis of local earthquake data for multi-layering (see Appendix). Standard abbreviations indicate geologic age of rocks; Tv = Tertiary volcanic rocks. Note that section in lower left is transverse to upper cross section. Datum for earthquake cross sections (below) is 1,500 m above sea level; transposition to upper section correspondingly adjusted. (See text regarding focal-depth precision.)

Figure C-4.

(from Arabasz and Julander, 1986) illustrating results from using portable seismographs in central Utah.

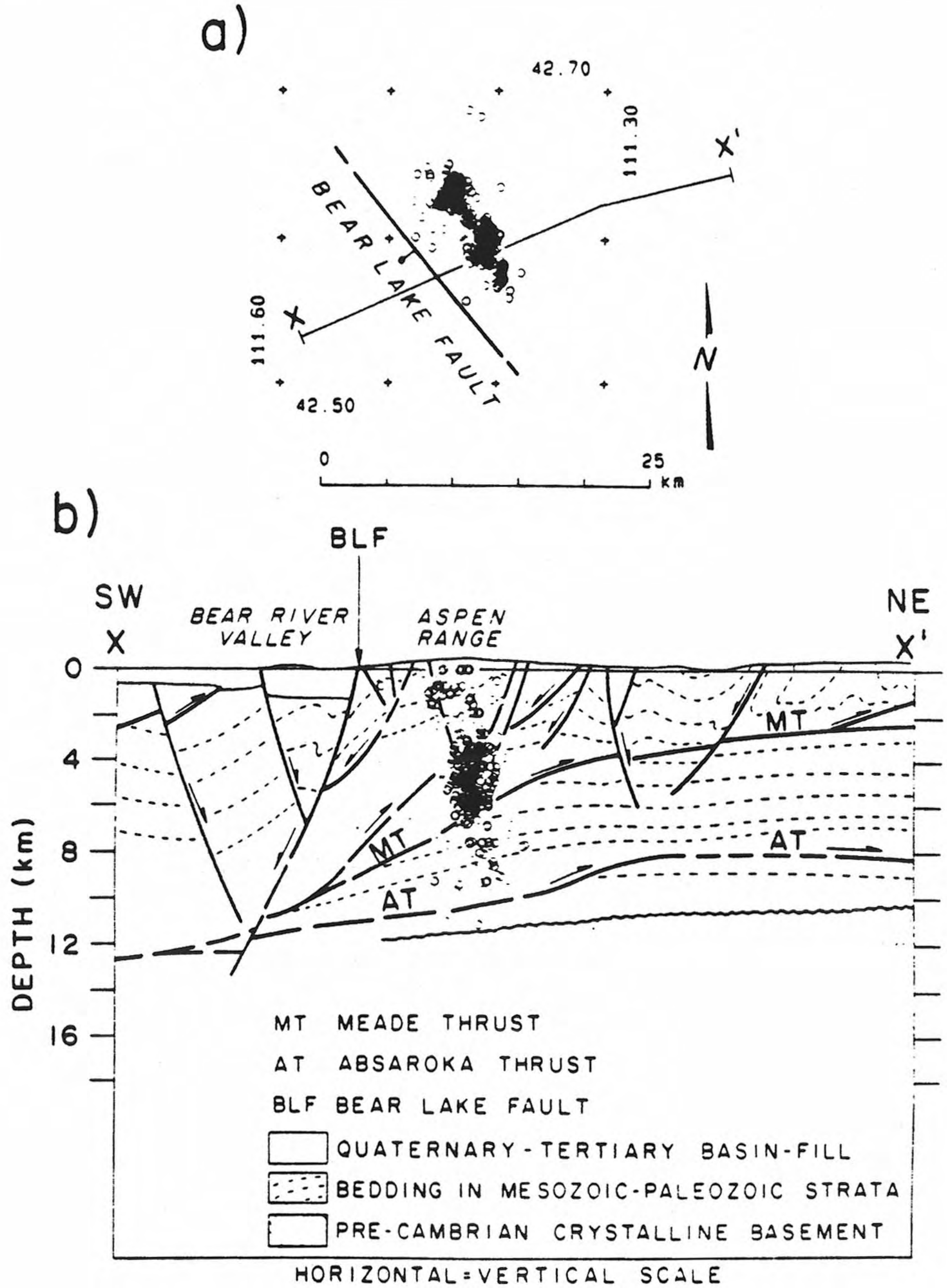


Figure 17. Association of swarm seismicity in late 1982 near Soda Springs, Idaho, with geologic structure. Earthquakes located by Richins and others (1983) are shown (a) in map view and (b) superposed upon a geological cross section (generalized after Dixon, 1982). Datum for the cross section is 1,700 m above sea level. Earthquake foci have a mean epicentral precision of 0.50 (±0.21) km and a mean focal-depth precision of 0.98 (±0.57) km.

Figure C-5.

(from Arabasz and Julander, 1986) showing the complex association of background seismicity with geologic structure and the apparent influence of low-angle detachments on focal depth distribution.

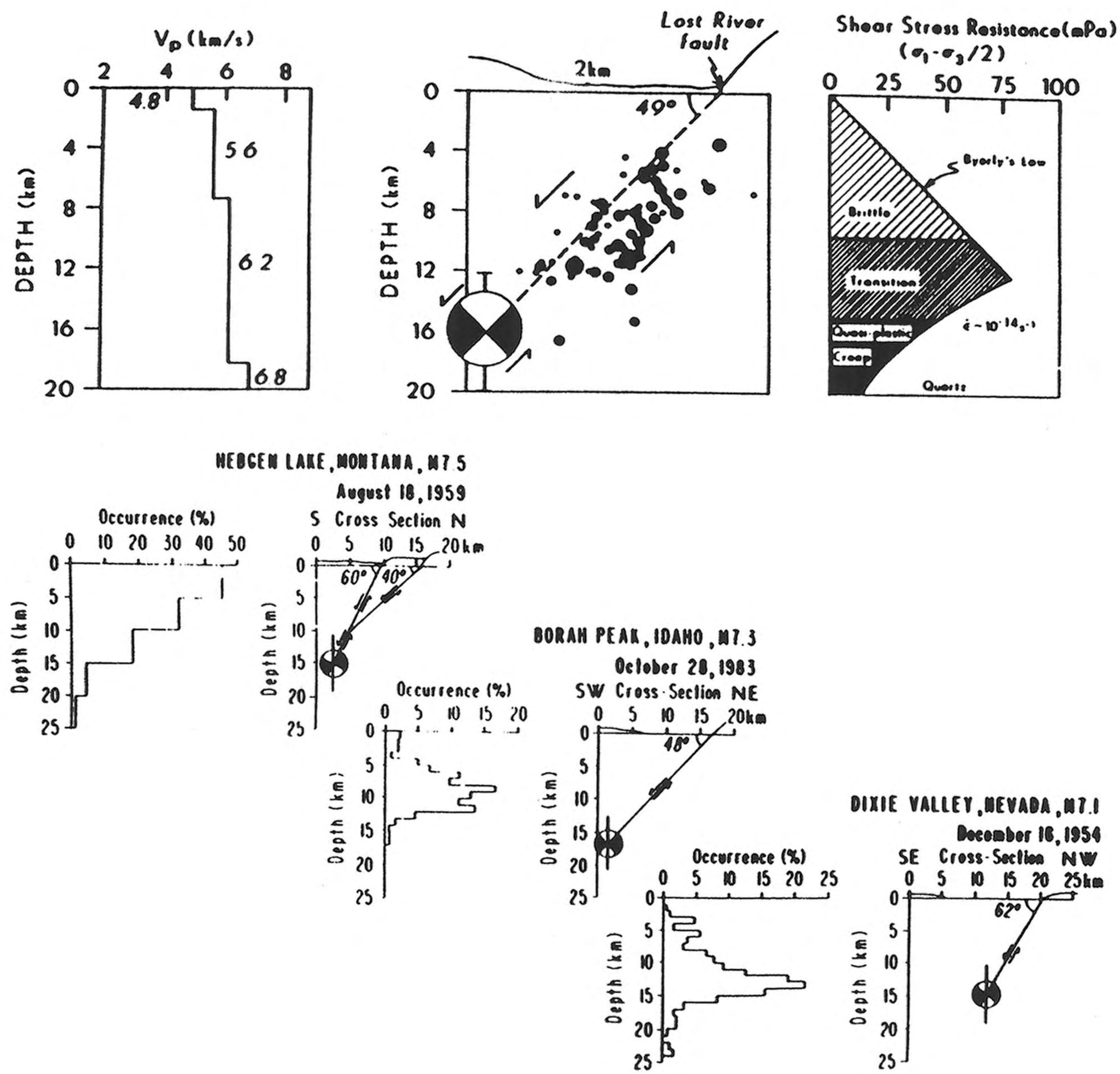


Figure C-6.

(from Smith and others, Bull. Seism. Soc. Am. , in press)

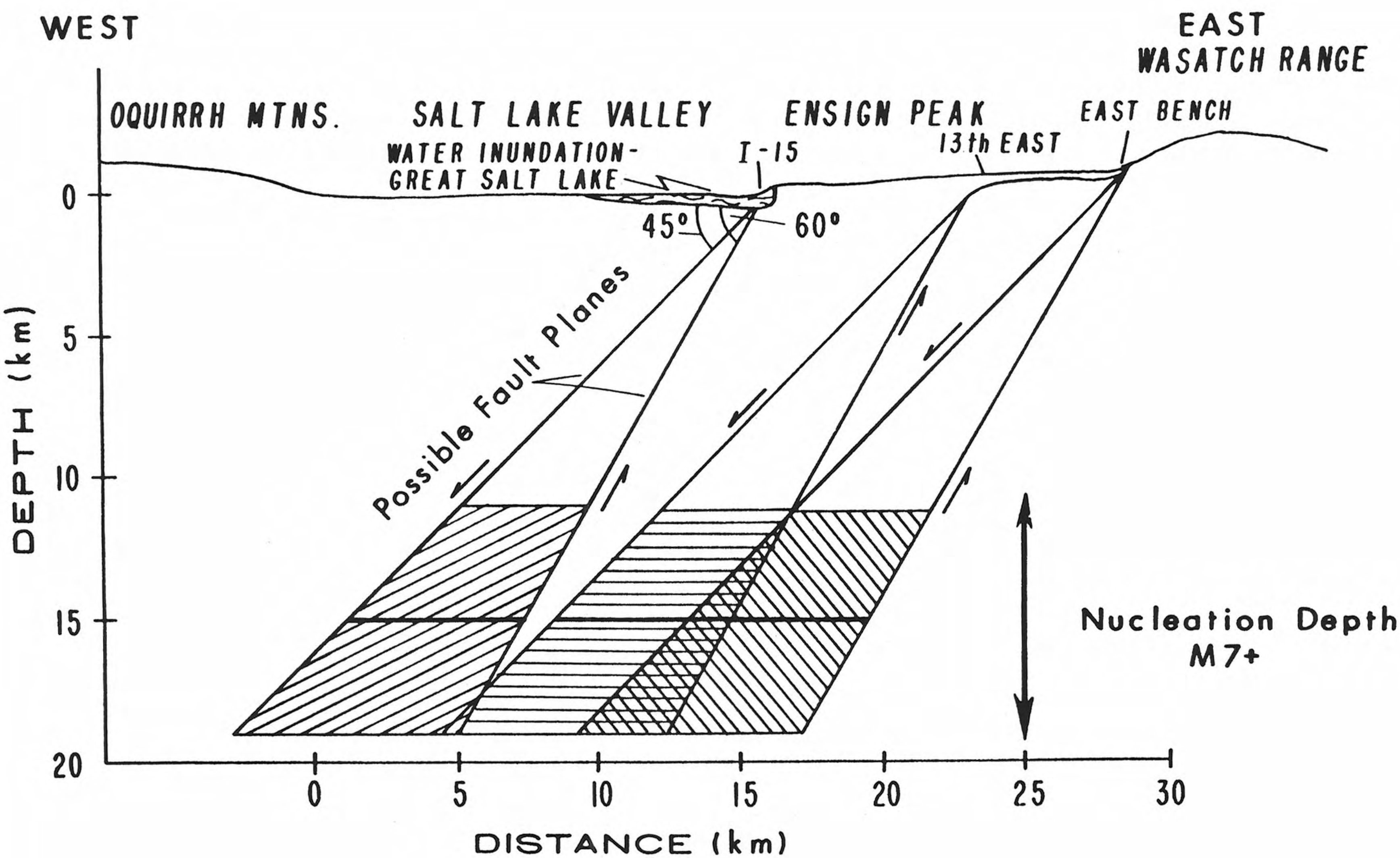


Figure C-7.

(from Smith and others, 1984, U.S. Geol. Survey Open File Rept. , 84-763)

REVIEWS OF GEOPHYSICS, VOL. 25, NO. 6, PAGES 1203–1207, JULY 1987
U.S. NATIONAL REPORT TO INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS 1983–1986

IRIS - A University Consortium for Seismology

STEWART W. SMITH

Incorporated Research Institutions for Seismology
Arlington, Virginia

IRIS is a university consortium organized to provide modernized seismographic networks and data distribution facilities for the university research community and funded by the National Science Foundation (NSF). There are currently 50 member institutions, each of which is represented on the Board of Directors. Overall policy and scientific guidance is provided by this Board acting through a 7-member Executive Committee and three 9-member Standing Committees representing each of the program elements. Technical and management support is provided by the President, and a Program Manager or Director for the three operational programs which are 1) Global Seismographic Network (GSN), 2) Portable Array Studies (PASSCAL), and 3) Data Management Center (DMC). This paper presents the historical background of development of IRIS and a review of current operational programs.

INTRODUCTION

The concepts for a university consortium in seismology developed in in early 1983 along two parallel but independent paths. One path was leading to an upgraded global digital seismographic network and the other to a revitalized national effort in seismological studies of the continental lithosphere. Recognition of common interests and improved opportunities for funding led to the merging of these two efforts beginning in late 1983 and culminating with the incorporation of IRIS in May, 1984.

HISTORICAL DEVELOPMENT

Path to the Global Seismographic Network

In the early 1980's, reductions in the U.S. Geological Survey (USGS) budget threatened the operation of the World Wide Standard Seismographic Network (WWSSN). Although this network had a history of being vulnerable during periods of budget contraction when it had been the responsibility of other government agencies, it had always survived. This time, however, it was more seriously threatened. Options that were discussed and presented to the community of seismologists that used this important resource included, for example, cutting back to only one component for long and short period seismometers at each station and abandoning or seriously delaying the modernization program that was already underway to convert selected stations to digital recording. As part of the seismological community's response, the National Academy of Sciences published a report [Committee on Seismology 1983a], urging the continued support and upgrading of the WWSSN. Considering the landmark significance that the WWSSN had played during the previous two decades, university seismologists were galvanized to action. The objective became not only to save the network but to take the initiative in insuring that it would be expanded and modernized.

In July 1983, an *ad hoc* group of 20 scientists representing 10 academic institutions met at Harvard University to discuss a major new initiative in Earth Sciences, whose key element would be the establishment of a standardized global network of digital telemetered seismographic stations. Following that meeting, an embryo organization formed to bring these ideas to a wider audience.

At about the same time, but independent of these activities, the Committee on Science, Engineering, and Public Policy (COSEPUP) of the National Academy of Sciences (NAS) briefed George Keyworth, then Science Advisor to President Reagan, on five broad "targets of opportunity" that had the capacity to provide a rapid advance in the near future and that would contribute most to our understanding of Earth's interior and history. These ideas came to be known as the COSEPUP Initiatives. Two of the initiatives presented were global seismographic networks and crustal seismology.

On September 29, 1983, a briefing was held at the National Academy of Sciences to acquaint representatives of some nine government agencies and the National Academy Committee on Seismology with the plans of the academic group. Then, October 20 and 21, 1983, a workshop was held in La Jolla which was attended by some 90 participants representing academic institutions, government agencies, national laboratories and other interested organizations. Several participants came from overseas, indicating a very broad interest in these plans.

At this meeting, presentations were made describing existing networks, the scientific requirements for the new global network, and some concepts as to what this new network might look like. The attending group then decided to organize itself more formally as the Senate of an organization they named the Associated Research Institutions for Earth Sciences (ARIES). They elected a Board of Trustees, and charged an Executive Committee with the task of preparing a draft of a proposal to implement these ideas.

Path to the PASSCAL Program

The parallel and complementary Lithospheric Seismology Program of the NSF was the outgrowth of more than three years of study by a NAS Committee on Seismology panel charged with defining scientific needs and objectives and assessing instrumentation requirements for high resolution three-dimensional seismic studies of the continental lithosphere. The panel's deliberations included two major open meetings on the technical means required to implement these proposed studies. Some 60 scientists from universities, industry and government agencies attended an NSF-sponsored workshop at the May 1983 meeting of the Seismological Society of America in Salt Lake City. A second workshop held in the fall, with NSF and IASPEI support, brought the international community (over 25 non-US par-

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ticipants) into the process of working toward appropriate instrumentation [Commission on Controlled-Source Seismology, 1983].

A comprehensive scientific justification and technical basis for a major new research program to study the continental lithosphere was contained in a report by the Committee on Seismology [1983b]. In this report was a recommendation that a consortium of research institutions be formed to undertake large-scale array seismic studies of the continental lithosphere. Following this recommendation, an informal organizational meeting was arranged under the auspices of Carnegie Institution on November 21 and 22, 1983. At that meeting plans were made for an open national meeting to be held in Madison, Wisconsin, in early 1984.

The Merger

The ARIES Executive Committee worked diligently during the month of November preparing a draft of a science plan for the new global network and exploring the possibility of merging this effort with the developing continental lithosphere group. At the next meeting of the ARIES Senate and Board of Trustees on December 7, 1983, the following resolution was adopted.

"The Senate resolves that a corporation of research institutions be formed to seek funding for major research efforts in the earth sciences, which will include the development and deployment of a permanent global digital network and a portable regional digital network, and the establishment of one or more national seismic data and computational centers, and the Senate empowers the Board of Trustees to begin the process of incorporation."

Work continued on the plan defining the scientific objectives of the global network. This was reviewed again by the Board at a meeting on January 5 and 6, 1984, resulting in a document entitled *Science Plan for a New Global Seismographic Network*, [IRIS, 1984a]. At about this time discussions were held leading to a new name for the organization. In anticipation of its subsequent incorporation, ARIES was renamed as the Incorporated Research Institutions for Seismology (IRIS).

Meanwhile, the national organizational meeting of those concerned with seismological studies of the continental lithosphere, which was held in Madison on January 13 and 14, 1984, marked the formal beginning of the Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL). The purpose of the national meeting was to review the field of lithospheric studies and to establish a consortium of institutions which would form the nucleus of a major new program in seismology to carry out studies of the earth using a large mobile seismic array. By the end of the two day meeting that objective had been achieved.

The meeting was attended by 78 scientists and engineers representing 54 educational and governmental organizations plus substantial industrial representation. A Senate for the consortium was formed, consisting of one member from each institution represented at the meeting, and a Senate President was elected. On the second day of the meeting the Senate elected an eight man Board of directors empowered to carry out the formal tasks of the consortium.

The Senate noted the Dec. 7, 1983 resolution of the renamed IRIS group, and authorized its Board to undertake the task of joining with that group and to take the appropriate steps to form a non-profit corporation for seismology. That Corporation would have as its combined objective to serve the seismological community by coordinating large-scale experiments, acquiring and maintaining large numbers of portable seismograph instruments, implementing a global digital network, and overseeing a center for data archiving and distribution.

With this motivation IRIS was incorporated in the state of Delaware on May 8, 1984, with 26 founding members. At the initial meeting of the Board of Directors on May 13th, Thomas V. McEvilly was elected Chairman of the Board and Acting President, Shelton Alexander as Vice Chairman, Gilbert Bollinger as Secretary, and Brian Mitchell as Treasurer. As of that date IRIS began to function through an active committee structure, with standing committees for each of the program elements. Adam Dziewonski was appointed Chairman of the GSN Standing Committee, Robert Phinney as Chairman of PASSCAL, and Shelton Alexander and Stewart Smith as Co-Chairmen of the DMC.

During the summer of 1984 there were a number of committee meetings, and workshops, including one held at Princeton July 12-19 at which 22 participants worked on development of the PASSCAL Science Plan, [IRIS, 1984b], and on plans for the Data Management Center. The culmination of these and all previous activities of the group was the preparation of a 10-year proposal to the National Science Foundation [McEvilly and Alexander, 1984], submitted in July 1984. Support for the ideas in this proposal was reflected broadly in the scientific community. Particularly timely and supportive were a number of National Academy of Science reports including that of the Committee on Opportunities for Research in the Geological Sciences [1983], the Committee on Seismology [1983a] the Panel on Data Problems in Seismology [1983], and the U.S. Geodynamics Committee [1983].

In the plans for development of the GSN, from the outset there has been close cooperation with the U. S. Geological Survey (USGS). In early 1984, a letter of agreement was signed by IRIS and the USGS specifying the individual and joint responsibilities of both organizations. Briefly summarizing this agreement, IRIS will be responsible for plans and priorities, scientific guidance, technology studies, and a scientific data center. USGS will be responsible for test and evaluation, station agreements, installation and training, network support, data collection, and earthquake information. The intent is to use the resources of both IRIS and the USGS so as to maximize the scientific benefits of the GSN. To facilitate this, the USGS is represented on the Standing Committee of GSN, and all its subcommittees, and each organization has designated both a program coordinator and a technical coordinator.

In response to these initiatives, NSF approved a small grant in April of 1985, for planning purposes, which made it possible to proceed with the development. Stewart W. Smith was appointed President and Chief Executive Officer in July 1985, and in October a corporate office was established in Arlington, Virginia. At this point the IRIS program finally began its transition from an all-volunteer committee operation to fully operational organization charged with developing the seismological facilities needed by the university seismological research community. Further details on operations and development from this point onward can be found in the IRIS Annual Reports [IRIS, 1985 and 1986]

Current Program

There are currently 50 member institutions in IRIS, each of which is represented on the Board of Directors. Overall policy

TABLE 1. IRIS Member Institutions, 1987

INSTITUTION	REPRESENTATIVE
University of Alaska	Nirendra N. Biswas
University of Arizona	Terry C. Wallace, Jr.
Boston College	John Ebel
California Institute of Technology	Don L. Anderson
University of California, Berkeley	Thomas V. McEvilly
University of California, Los Angeles	Paul M. Davis
University of California, San Diego	John A. Orcutt
University of California, Santa Barbara	William A. Prothero, Jr.
University of California, Santa Cruz	Karen C. McNally
Carnegie Institution of Washington	Selwyn I. Sacks
Columbia University	Paul G. Richards
Cornell University	Bryan L. Isacks
University of Colorado, Boulder	Carl Kisslinger
Georgia Institute of Technology	Leland T. Long
Harvard University	Adam M. Dziewonski
University of Hawaii at Manoa	Charles Helsley
University of Illinois at Urbana-Champaign	Wang-Ping Chen
Indiana University	Gary L. Pavlis
Massachusetts Institute of Technology	Thomas H. Jordan
Memphis State University	Jer-Ming Chiu
University of Michigan	Thorne Lay
Michigan Technical University	Gordan E. Frantti
University of Minnesota	F. R. Schult
University of Missouri	Thomas J. Owens
New Mexico Inst. of Mining & Tech.	John S. Knapp
State Univ. of New York, Binghamton	Francis T. Wu
State Univ. of New York, Stony Brook	Clifford H. Thurber
Northern Illinois University	Phillip Carpenter
Northwestern University	Seth A. Stein
University of North Carolina	Christine A. Powell
Oregon State University	William Menke
Pennsylvania State University	Shelton S. Alexander
Princeton University	Robert A. Phinney
Purdue University	Lawrence W. Braile
Rice University	Alan R. Levander
Saint Louis University	Brian J. Mitchell
University of South Carolina	Richard T. Williams
Southern Methodist University	Eugene T. Herrin
University of Southern California	Ta-Liang Teng
Stanford University	George A. Thompson
Texas A&M University	Melvin Friedman
University of Texas at Austin	Arthur E. Maxwell
University of Texas at Dallas	George McMechan
University of Texas at El Paso	G. Randy Keller, Jr.
University of Utah	Robert B. Smith
Virginia Polytechnic Institute	Gilbert A. Bollinger
University of Washington	Robert S. Crosson
University of Wisconsin - Madison	Robert P. Meyer
University of Wyoming	Scott B. Smithson
Washington University, St. Louis	Douglas Wiens

and scientific guidance is provided by this Board acting through a 7-member Executive Committee and three 9-member Standing Committees representing each of the program elements. The makeup of the Board is shown in Table 1.

Technical and management support is provided by a staff consisting of the President, and a Program Manager or Director for each of the three operational programs. The status of each of these programs and the plans for the future are reviewed below.

Global Seismographic Network (GSN)

A site selection subcommittee of the Standing Committee for the Global Seismographic Network prepared a report [SCGSN, 1986] recommending specific sites for 51 new or upgraded digital seismograph stations over the next five years. To provide international coordination for this plan, IRIS has become a founding member of the recently organized Federation of Broad Band Seismic Networks described by Dziewonski and Romanowicz [1986]. This organization should provide an effective means for coordinating station siting, establishing instrumentation standards, and facilitating international data exchange.

The basis of the GSN siting plan was to have uniform global coverage to the extent that is feasible. For this purpose, the Earth's surface was divided into 128 equal area regions, corresponding to squares with dimensions of 18 degrees at the equator. An exercise that was carried out demonstrated that about 90% these blocks are suitable for seismograph stations, and made clear that if uniform global coverage is the objective, a good deal of emphasis needs to be placed on Pacific island sites. The list of sites that was recommended includes 39 existing stations as well as 12 new stations. Ten of the new stations would be located on islands in an attempt to improve oceanic coverage. In addition, a higher density of deployment is envisaged in the continental United States, with perhaps 10-12 GSN stations to be deployed there.

A development contract will be in place by March 1987 for production of prototype data-logging systems that satisfy the requirements put forth in *Design Goals for a Global Seismographic Network*, [SCGSN, 1985]. These systems will provide greatly improved data when they become available in 1988. In order to move ahead with upgrading the global network, some interim steps are being taken that will provide additional high quality digital data from selected stations.

DWWSSN Upgrades. Five sites have been selected for upgrading with Streckeisen seismometers in 1986 and early 1987. They are all DWWSSN sites, with digital data logging facilities available, so that the upgrade can be made with only minor modifications to the existing facility. Since the original sensors at these sites along with their normal analog recording will no longer be available, systems for digital simulation to produce visible recordings with the characteristics of these familiar instruments will have to be provided. This work is being funded by IRIS and implemented by the Albuquerque Seismological Laboratory of the USGS. The stations are Afiamalu (South Pacific), Quetta (Pakistan), Kevo (Finland), Toledo (Spain), and College (Alaska).

WWSSN Upgrades. Several sites may be upgraded in 1987 using data loggers similar to those developed at Harvard, [Steim, 1986]. These systems, designated as IRIS-I, include many of the features described in the IRIS Design Goals and should provide high quality new digital data for an interim period while the final IRIS-II systems are being developed. They feature 24-bit analog to digital converters with a 68020 based computer for digital filtering, data buffering, and dial-up capabilities for data transmission.

Effective in 1987, IRIS will take over the responsibility for funding the International Deployment of Accelerometers (IDA) project operated by the University of California at San Diego (UCSD) with the objective of upgrading it and integrating it into the GSN. The IDA equipment [Agnew et al ,1986] installed at many WWSSN stations as well as at some independent sites, has provided an important basis for much of the research work in low frequency seismology over the past decade. Since the equipment consists of a single vertical component instrument (LaCoste-Romberg gravimeter), which is sampled only once per 10 seconds, these instruments will be replaced with 3-component broad band systems as soon as is practical.

A new station in the IDA network of gravimeters is currently being installed on Easter Island. IRIS is cooperating with the UCSD and is providing additional funding such that the piers and facilities here can be made suitable for an eventual installation of a 3-component set of seismometers. Work is currently underway in constructing the vault. Since this is a fairly remote station, full development of an IRIS/IDA station will await an evaluation of the initial operating experience and technical support that is available on the island. This experience is of particular importance, since an early priority for IRIS is the development of other Pacific island stations such as Wake, Johnston, Kwajalein, and Midway. Noise conditions for horizontal component instruments are likely to be such that borehole installations may be necessary at these island sites.

A Data Collection Center to process data from this new network is being jointly developed by IRIS and the USGS at the Albuquerque Seismological Laboratory. When complete, it will be capable of processing a high volume of continuous broadband data from 100 stations, arriving either by telemetry or by mail, and transmitting it to the IRIS Data Management Center.

Portable Array Studies (PASSCAL)

Instrument Development. The PASSCAL Science Plan [IRIS, 1984b] spelled out in detail the need for an advanced portable seismograph system. The instrument envisaged would be digital, with high dynamic range and very low power requirements, and most importantly, it would be flexible and modular so as to be able to adapt to changes in technology that are likely to occur over the lifetime of the instrument. Since the plan is to make a major national commitment through the purchase of 1000 instruments, it is clear that we should not freeze in place the technology available at this particular point in time. The rapidly changing field of mass storage illustrates the most obvious example of this problem, but comparable changes in encoder technology, timing systems, and virtually every other part of the system are very likely over the next decade. To avoid obsolescence resulting from changing technology, a plan was made to evaluate the feasibility of communications bus approach to the design. With this concept, the seismic instrument might functions as a local area network, with each module being independent and able to communicate with the other modules in the system. A successful system of this sort could stave off obsolescence for a long period of time, by simply accommodating new modules as both the requirements for experiments and the technology change.

A development program was undertaken, with NSF support through the Carnegie Institution of Washington, in the year before IRIS obtained its first funding. The approach taken, under contract with the University of California at Los Angeles was a micro-power adaptation of a standard industry communications bus. The hardware for this system, referred to as the PASSCAL Bus Interface (PBI), was completed in the fall of 1985, and a demonstration of a modular system using the PBI was successfully carried out in September, 1986.

A request for proposals for development of the PASSCAL field instrument was released in October 1986. It was written with sufficient flexibility that bidders were able to make their own judgments regarding whether or not to use the PBI in the systems that they proposed. Although as of the date this manuscript was prepared, final decisions on the instrument procurement have not been made, it was clear that the PBI as originally envisaged would not be used by manufacturers. Suitable industry sponsored approaches to the problems of low-power, modularity, and upgradeability emerged, due in part to the participation of industry in the PBI project. Final evaluation of industry proposals is expected to be complete by February 1987.

Ouachita Experiment. Since the development time for PASSCAL instruments is foreseen as at least 3 years, in order to avoid a significant loss of momentum among the researchers in this area, a plan was developed for interim field experiments utilizing existing equipment. The first of these was carried out with leased equipment during May, 1986, in the Ouachita Mountains of southern Arkansas. The objective here was to study the deep structure of the buried Ouachita orogenic belt. In this experiment, the full wavefield was recorded with two deployments of 400 digital group recorders over a 200 km profile. The data collection featured wide bandwidth, 250 m station spacing, long offsets, and multiple explosive sources. With this data, and modern processing and interpretation methods, we can address some fundamental questions in this region concerning the Paleozoic continental margin, the presence of oceanic or continental crust, and the possibility of an ancient remnant of subducted lithosphere.

Basin and Range Experiment. The Basin and Range Province of western U.S. is a major continental rift zone, characterized by widespread Cenozoic volcanism and extension. It is a composite of individual grabens and half-grabens rivaled in extent only by the East African Rift. A number of plate tectonic models have been proposed to explain these features, but the data with which one can test and evaluate competing hypotheses is not yet available. To explore the crust and mantle structure in this area, PASSCAL co-sponsored a seismic reflection-refraction experiment in July, 1986, together with the USGS and the Air Force Geophysical Laboratory. Twenty eight shots, as large as 2500 kg, were detonated along a 300 km E-W line through Lovelock, Nevada, and along a 200 km cross line. Seventeen organizations participated in this experiment, involving nearly 200 independently recording systems and 384 channels of reflection recording equipment. Preliminary results of the experiment were presented by Keller et al [1986] and by Thompson et al [1986] together with a large number of papers at a special poster session held at the 1986 AGU meeting in San Francisco.

Data Management Center (DMC)

A workshop was held at NCAR in February 1986 for the purpose of defining the IRIS requirements for a data management system. The workshop report [Minster and Goff, 1986] was then used as an element of a solicitation for a detailed design study. This design study is now underway, with an expected completion date of March 1987. To serve the diverse needs of the user community, it seems clear that neither a fully centralized system nor a fully decentralized one is appropriate. With advances in low cost mass storage, communications, and computing capabilities, interest is focusing on the possibility of a hybrid system making use of the best features of both types of systems.

International Data Exchange. An important element of the IRIS Data Management Center will be to provide a convenient means of interchange of data with operators of other national and international networks such as the French effort known as GEOSCOPE [Romanowicz et al, 1984], and data centers such as that proposed by the Observatories and Research Facilities for European Seismology [Nolet et al, 1986]. Coordination between these and other international efforts will be facilitated by the recently organized Federation of Broad Band Digital Seismographic Networks [Dziewonski and Romanowicz, 1986], an organization affiliated with both International Lithosphere Program and and IUGG. This Federation will provide a forum for coordination of global station siting, recommendation of standards for data formats, and other important matters affecting the quality of the international data set.

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Appendix C-2

Description of the PASSCAL Portable Digital Seismograph

excerpted from

"PASSCAL INSTRUMENTATION" by J. Fowler,
PASSCAL NEWSLETTER
(December 1988)

PASSCAL INSTRUMENT

The PASSCAL Instrument as constructed by Refraction Technology Inc. represents a significant change in portable seismic instrument technology. This instrument was designed to record everything from conventional seismic reflection profiles to long-term broadband deployments in support of the Global Seismic Network. The instrument, the auxiliary recording system and the field computer were designed to enable a small group of researchers to support a large number of instruments in the field at one time.

The PASSCAL System consists of four major subsystems. Figure 1 shows a diagram of the PASSCAL System Components.

The Data Acquisition Subsystem (DAS) is the basic recording subsystem. It takes the signals from up to six sensors and digitizes the signal, performs event detection when necessary and stores the data in an internal 4 Mbyte memory.

The Time Keeping Subsystem mounts on top of the DAS unit and provides an external clock signal which synchronizes data samples to a common time base. The specifications for the timing system call for an array of recorders to be synchronized relative to one another to within 1 ms. The absolute time accuracy is to be within 10 ms of Universal Time. A GOES receiver and two types of Omega receivers are being tested.

The Auxiliary Recording Subsystem (ARS) is currently a portable tape unit which is carried to the field to collect data from multiple DAS units, thus permitting them to remain installed in the field. The ARS utilizes a helical scan tape unit which can store 2000 Mbytes of data on a tape. By utilizing the SCSI port available in the ARS, it is possible to change to new mass storage units as technology improves.

The final part of the system is the Field Set-Up Terminal. This is a small hand-held terminal which will be carried to the field and used by the operator to communicate with both the DAS and the ARS. The operator can down-load all of the set-up parameters, run self-checks and calibrations, and modify instrument performance through this unit. It can be used to display data, check geophone installation, and check general system performance. Two different types of terminals are supported. The first is the Epson Terminal which is a small light weight unit which can easily be used in rugged terrain. The second is laptop PC.

The DAS has six input channels. If channels 4-6 are not being used the supply voltage to the analog section of these channels is turned off to save power. Each of the six channels is sampled with 16 bit resolution at a rate of 1000 samples per second. The signals are then passed to the Digital Signal Processor where they are filtered and decimated to the final output sample rates for the various data streams. The Digital Signal Processor operates with 32 bits of resolution, thus through the process of filtering and decimating it is possible to have more than 16 bits of resolution at the lower sample rates.

The concept of the Data Stream is unique to this instrument. The instrument can handle up to eight data streams. Each data stream consists of from one to six input channels sampled at a given sample rate and activated by a specified trigger. As an example Data Stream 1 could consist of channels 1-3 sampled at 200 samples per second with an event trigger designed to local events. Data Stream 2 could consist of channels 1-3 sampled at 20 samples per second with an event trigger designed for teleseismic events. Data Stream 3 could be channel 1 recorded continuously at one sample per second. There is no restriction on which input channels can be connected to a given data stream. All channels in the stream will have a common sample rate in that data stream. There are several different triggers which can be used to activate a data stream. These are:

- Event trigger,
- Radio or External trigger,
- Timmed trigger,
- Continuous trigger, and
- Cross trigger.

The cross trigger allows one data stream to be triggered by the activation of a trigger on another stream. With this concept, each data stream is like having a separate instruments in the field. It is possible to conduct multiple experiments within a single instrument.

Another different feature of this unit is in the fact that the sampling is synchronized to an external clock if one is present. In the past, when an external clock was present it was recorded on an auxiliary data channel, and any timing corrections were made during post-processing. Because this correction is a labor intensive task, it was not always done. The PASSCAL instrument is synchronized to the clock. Each sample is time tagged with the correct time as it is taken. Thus all of the data have the correct time as they are read into the field computer. This type of system is a necessity if many instruments are to be deployed at a single time.

The PASSCAL Instrument is designed with a Small Computer System Interface (SCSI) port as standard feature. This port gives the instrument the capability to be used in many different types of environments. The port acts as the standard upload port for data to be transferred from memory to the ARS. The speed of this transfer is extremely fast and a typical upload of 4.5 Mbytes to the tape recorder takes about 2 minutes. The port also allows SCSI devices to be installed in the box for long-term deployments. Five of the prototype units have 200 Mbyte disks installed in the battery compartment of the unit. In deployments where external power such as solar cells is being used, the disk gives the unit about 200 Mbytes of storage. This allows service intervals to be extended to once every two to four weeks. The disk is powered only when it is being written to, so that the overall increase in power necessary to operate is minimal. The data can be uploaded to the tape unit by execution of a SCSI copy command. This can take place quickly without the need of CPU intervention of the recording system.

The SCSI port allows the PASSCAL instrument to utilize any mass storage system that has a SCSI port. Currently this includes magnetic and optical disks as well as several different tape units. The major market for this technology is PC industry so that developments are rapid and we can take advantage of the cheaper pricing of this market. The PASSCAL instrument is not tied to any one kind of mass storage medium. Currently none of the mass storage units are specified to operate below freezing, therefore, if the units are to be deployed in freezing conditions it is best to plan on using the solid state memory as the recording medium.

Two additional features of the system are first all non-data related happenings including operator communications are logged in a State of Health channel with the data. This State of Health channel is uploaded with the data and it provides a record of what went on in the instrument. Secondly, all communications between the Hand Held Terminal including uploading of the data can be accomplished without stopping data acquisition. This allows the operator to check instruments a look at event directories without interfering with the data gathering activities of the instrument.

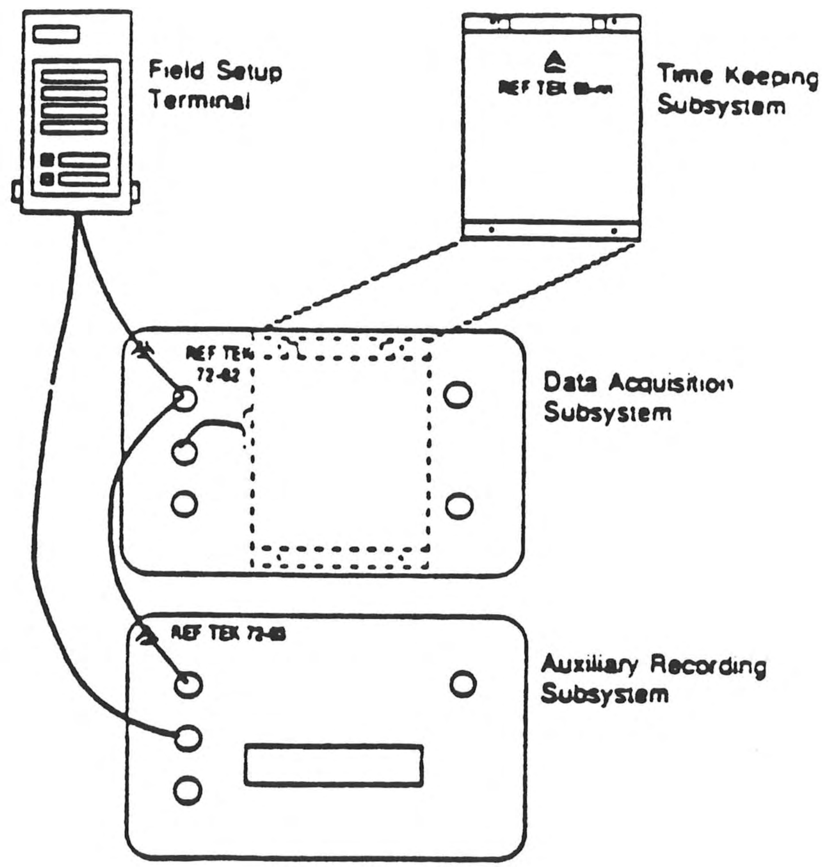

Figure 1 System Components

The Magnitude 5.3 San Rafael Swell, Utah Earthquake of August 14, 1988:

A PRELIMINARY SEISMOLOGICAL SUMMARY

by S. J. Nava, J. C. Pechmann and W. J. Arabasz
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Department of Geology and Geophysics

On August 14, 1988, an M_L (local magnitude) 5.3 earthquake occurred in central Emery County, Utah, at 2:03 PM (MDT). The epicenter of the shock—the largest earthquake to occur in the Utah region since the 1975 M_L 6.0 Pocatello Valley earthquake—was in an unpopulated area of east-central Utah on the northwest edge of the San Rafael Swell (figure 1). The epicenter was located 20 km southeast of Castle Dale (the nearest town) and 55 km south of Price. The earthquake was felt strongly throughout central Utah (Modified Mercalli intensity V to VI), where it caused some minor damage, and was reported felt as far away as Golden, Colorado, and Albuquerque, New Mexico (U.S. Geological Survey, 1988).

Historically, the two largest earthquakes in east-central Utah were both of estimated magnitude 4.3. They occurred 70 km northwest of Moab in 1953 and 50 km east of Price in 1961. Instrumental monitoring by the University of Utah since 1962 has shown sparse seismicity in the area of the San Rafael Swell, although locally intense microseismicity characterizes coal mining areas of the eastern Wasatch Plateau to the northwest. Shocks of M_L 3.1 and 3.0 occurred within 20 km of the August 14 main shock, in 1962 and 1964, respectively. Prior to August 14, the epicentral area had not experienced any earthquakes large enough to be detected by the University of Utah's regional seismograph network since January of 1988, when a swarm of seven events ($M_L \leq 2.5$) occurred there. On August 14, six foreshocks of magnitude 1.8 to 3.8 occurred during the 65 minutes prior to the M_L 5.3 main shock. The two largest foreshocks, of M_L 2.9 at 12:58 PM (MDT) and of M_L 3.8 at 1:07 PM (MDT), were felt in nearby small towns (U.S. Geological Survey, 1988).

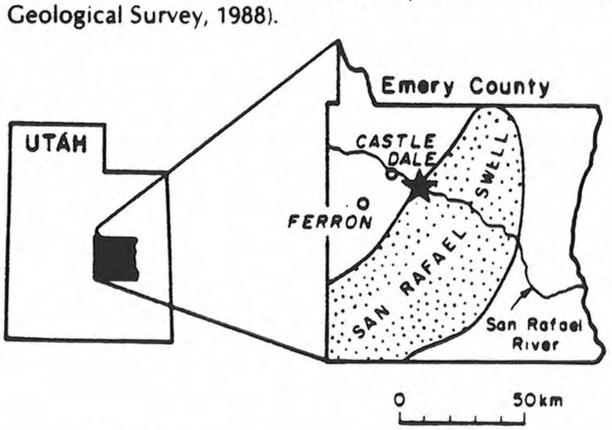


Figure 1. Reference Map depicting the geographic location of the August 14, 1988 San Rafael Swell, Utah earthquake sequence. The star represents the location of the main shock.

The University of Utah has located 147 earthquakes associated with the San Rafael Swell sequence that occurred from August 14 through September 30, 1988. The parameters of the five largest earthquakes of the sequence are described in table 1. Through September 30, there were 24 earthquakes of magnitude 2.0 and larger. A plot of earthquake magnitude vs time (figure 2) indicates a typical foreshock-main shock-aftershock sequence.

The nearest seismograph station at the time of the August 14 main shock was a permanent station of the University of Utah seismograph network located 20 km to the east at Cedar Mountain. Beginning the day after the main shock, the University of Utah installed five portable seismographs in the epicentral area (triangles, figure 3). Four temporary seismograph stations, directly linked to the University of Utah central recording lab in Salt Lake City, were installed on August 20 and 21 (inverted triangles, figure 3). These stations supplemented the portable seismographs until August 31, when the latter were removed. The telemetered stations continue to operate as of mid-November, 1988.

The local seismograph stations provide excellent control on the locations of aftershocks that occurred after 7:10 PM (MDT) on August 15. The locations of some of the earlier events in the sequence, particularly the focal depths, are less well constrained. For this reason, we have fixed the depth of the main shock and several events to 14 km (see table 1), a depth close to that of the deepest

TABLE 1

SAN RAFAEL SWELL, UTAH, EARTHQUAKE SEQUENCE
$M_L \geq 2.9$

DATE (1988)	ORIGIN TIME (UTC)	LATITUDE (°N)	LONGITUDE (°W)	DEPTH (km)	MAGNITUDE M_L (UU)	M_L (NEIS)	m_b (NEIS)
8/14	18:58:36.8	39°07.67′	110°50.10′	14.0R	2.9	3.5	--
8/14	19:07:58.8	39°07.51′	110°50.07′	14.0R	3.8	4.3	--
8/14	20:03:03.9	39°07.25′	110°50.28′	14.0R	5.3	--	5.5
8/15	14:50:23.5	39°07.59′	110°50.39′	14.0R	3.0	3.5	--
8/18	12:44:53.5	39°07.49′	110°50.72′	11.6	4.4	--	4.6

UTC (Universal Coordinated Time) = MDT + 6 hours

R = Restricted Focal Depth

M_L = Local Magnitude

m_b = Body Wave Magnitude

UU = University of Utah Seismograph Stations

NEIS = National Earthquake Information Service, Golden, Colorado

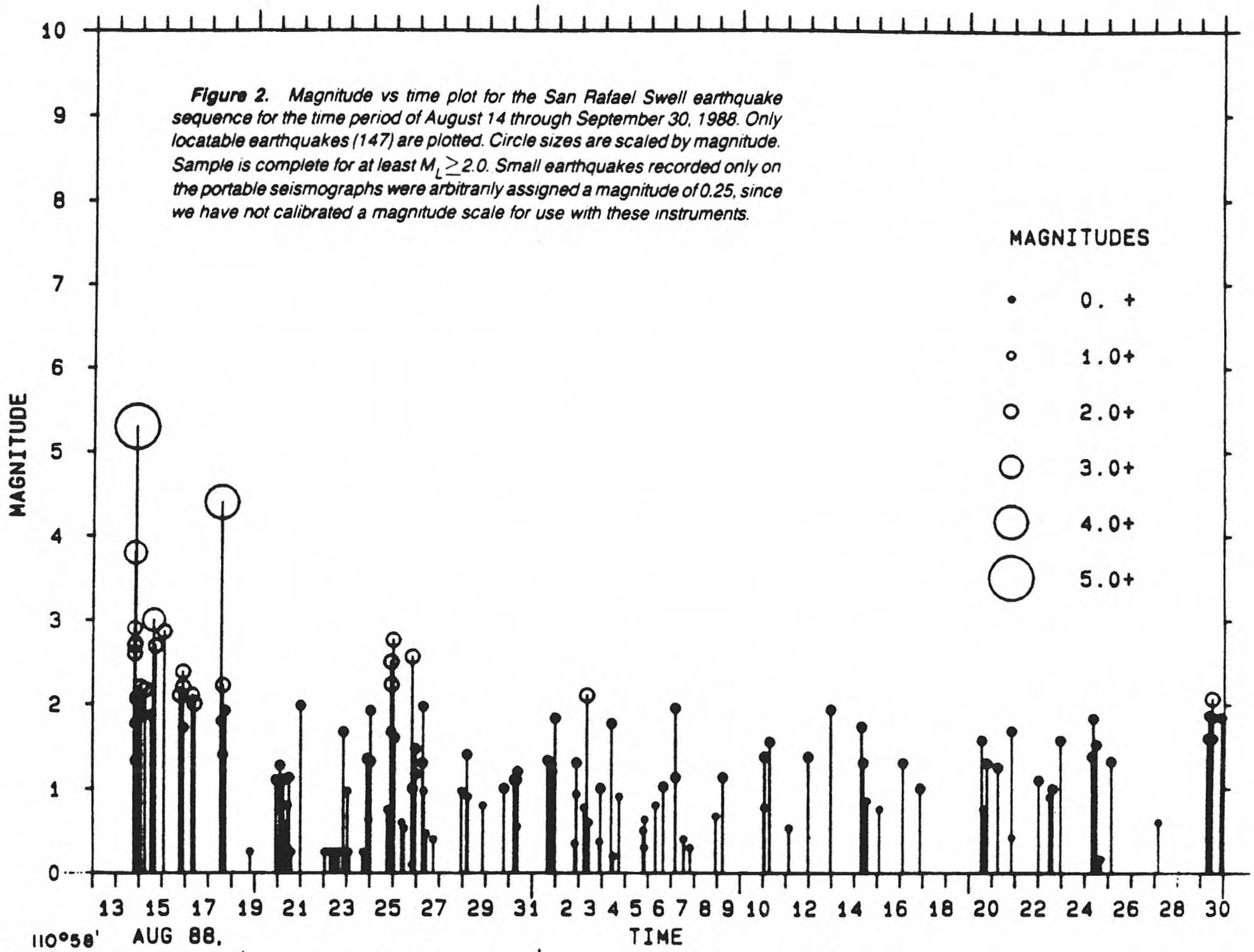


Figure 2. Magnitude vs time plot for the San Rafael Swell earthquake sequence for the time period of August 14 through September 30, 1988. Only locatable earthquakes (147) are plotted. Circle sizes are scaled by magnitude. Sample is complete for at least $M_L \geq 2.0$. Small earthquakes recorded only on the portable seismographs were arbitrarily assigned a magnitude of 0.25, since we have not calibrated a magnitude scale for use with these instruments.

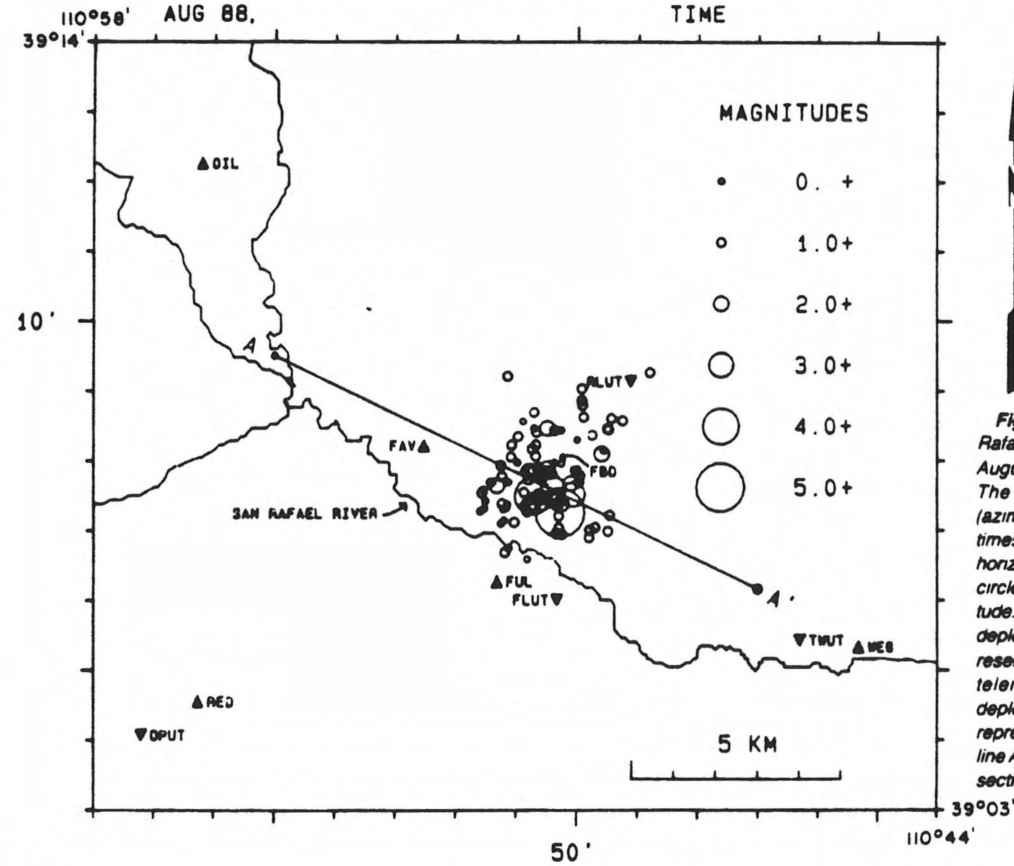
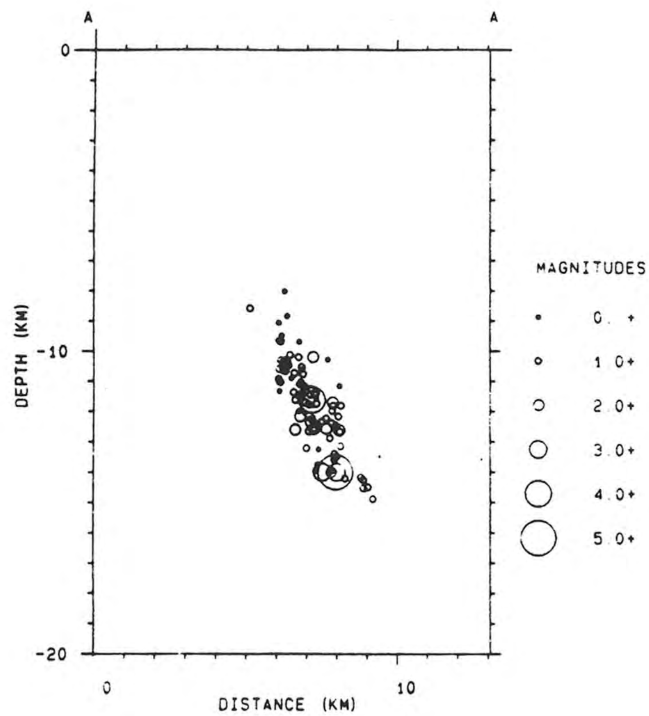


Figure 3. Epicenter map of the San Rafael Swell earthquake sequence from August 14 through September 30, 1988. The 91 best located earthquakes (azimuth gap $\leq 180°$, number of arrival times used in location ≥ 6, vertical and horizontal error ≤ 1.5 km), are plotted as circles, with the sizes scaled by magnitude. Portable seismograph stations, deployed from August 16-31, are represented by triangles, and the temporary telemetered seismograph stations, deployed from August 20 to present, are represented by inverted triangles. The line A-A' shows the direction of the cross section in figure 4.

well-located aftershocks. Figure 3 is an epicenter map of 91 of the best located earthquakes in the sequence. In map view, the earthquakes occupy a 3 x 4 km zone, adjacent to the main shock epicenter, elongated slightly in a north-northeast direction. In three dimensions, the hypocenters define an aftershock zone extending from 8 to 15 km depth and dipping 60° - 70° east-southeast, with a length along strike of 4 km and a downdip extent of 8 km.

The focal mechanism for the main shock is unfortunately not well constrained by the P-wave first motion data that we have acquired to date (figure 5). We are in the process of obtaining additional data from seismograph stations operated by other institutions, which should help to constrain the solution. The data presently available require one nodal plane to strike southeast and dip 50° - 75° southwest and the other nodal plane to strike north-northeast to northeast and dip between 40° east-southeast and 75° northwest. If the latter nodal plane is assumed to dip 60° east-southeast, parallel to the aftershock zone, then the resulting focal mechanism shows oblique normal faulting with a rake angle of -35° (solid lines, figure 5). Despite the uncertainty in the nodal plane orientations, the T axis of the main-shock focal mechanism is constrained to have a shallow plunge and an azimuth within 25° of east-west. The focal mechanism for the largest aftershock indicates oblique normal faulting on a plane that dips either to the east or southwest, and has a shallowly plunging T axis oriented N60°E-S60°W (±10°).

Figure 4. Hypocentral cross section, with no vertical exaggeration, of the earthquakes of figure 3, taken along line A-A.' Circle sizes are scaled by magnitude.



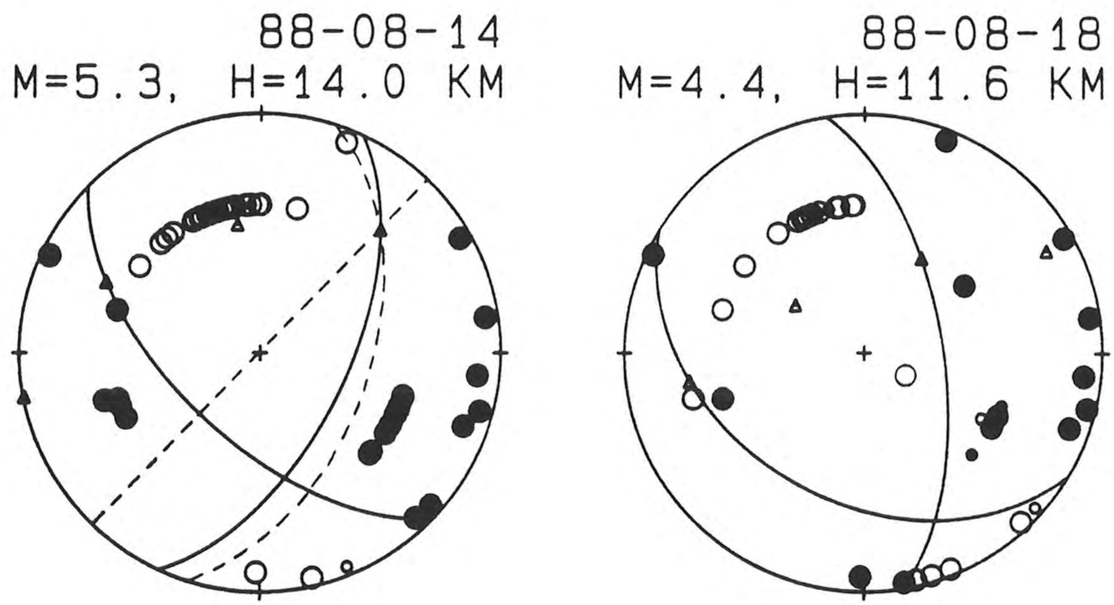


Figure 5. Preliminary focal mechanisms for the M_L 5.3 San Rafael Swell earthquake and its largest aftershock (M_l 4.4). P-wave first motions are plotted on a lower hemisphere projection, with compressions shown as solid circles and dilatations shown as open circles. The triangles show slip vectors and P and T axes. The focal depth (H) of the main shock is not very well constrained, and was fixed at 14 km to compute the focal mechanism. The first motion plot is not very sensitive to the assumed focal depth. We have drawn our preferred solution for the main shock focal mechanism (solid lines) to have one nodal plane parallel to the aftershock zone, with a strike of 25°, dip of 60°, and rake of -35°. The dashed lines show two of the alternative orientations for the northeast-striking nodal plane that are allowed by the first motion data if the southeast-striking nodal plane is held fixed. For the aftershock, the east-dipping nodal plane has a strike of 351°, a dip of 63°, and a rake of -62°.

The relatively deep focal depths of the earthquakes of the San Rafael Swell sequence, together with the main-shock focal mechanism, are important for attempting to correlate the earthquakes with local geologic structure. No surface faulting associated with the San Rafael Swell earthquakes has been reported, although no one, to our knowledge, has thoroughly searched the epicentral area. The fact that all of the well-located aftershocks are between 8 and 15 km in depth suggests that the earthquake rupture was confined to this depth range and did not penetrate to the surface. The apparent absence of surface faulting is consistent with a threshold magnitude of about 6.0 to 6.5 for surface faulting in the Utah region (Arabasz and others, 1987).

The depth of the San Rafael Swell earthquakes places them within Precambrian basement; gently-dipping sedimentary cover rocks of Mesozoic and Paleozoic age are about 3 km thick in this area (e.g., Neuhauser, 1988). Jurassic and Cretaceous strata in this part of the San Rafael Swell are known to have been affected by east-verging imbricate thrust faulting of Sevier-age deformational style (Neuhauser, 1988), but this shallow faulting did not involve Precambrian basement. Northwest- and northeast-trending basement fracture zones appear to provide important structural control on crustal blocks within the Colorado Plateau (Davis, 1978). Such basement faults presumably controlled the Laramide development of the San Rafael swell as a broad anticlinal upwarp with a monoclinal flexure on its southeastern flank some 65 million years ago (Davis, 1978; Stokes, 1986).

Geological maps of the San Rafael Swell (e.g., Hintze, 1980) show faults of north-northeast and northwest trend cutting Mesozoic rocks in the general vicinity of the recent earthquake activity. Data in hand suggest the association of the 1988 San Rafael Swell earthquake with buried slip on a Precambrian basement fault striking north-northeast and dipping moderately to steeply to the east-southeast. The aftershock distribution and magnitude versus fault length relations suggest that the causative fault need not be more than several kilometers long. Focal mechanisms imply a response to horizontal extension in a roughly east-west direction. This is similar to contemporary deformation inferred for the Basin and Range-Colorado Plateau transition to the west (Arabasz and Julander, 1986), but at variance with the north-northeast — south-southwest to northeast-southwest extension recently discovered to characterize the interior of the Colorado Plateau (Wong and others, 1987; Wong and Humphrey, 1988).

Earthquakes of moderate size ($M_L \leq 6.5$) are capable of causing considerable damage in urban areas, as evidenced by the M_L 5.9 Whittier Narrows earthquake that struck southern California on October 1, 1987 (Hauksson and others, 1988). The occurrence of the M_L 5.3 San Rafael Swell earthquake in an area where there are no active faults mapped at the surface and where historical earthquake activity has been minimal emphasizes the potential for moderate but potentially damaging earthquakes on buried faults anywhere in the Utah region—including the Colorado Plateau.

Acknowledgements— We thank Ted Olson and Allan Stevens of Snow College and Erwin McPherson, Ken Whipp, Julie Shemeta, and Mary Murphy of the University of Utah for installing and operating seismograph instrumentation in the field. Linda Hall of the University of Utah timed the records of the portable seismographs. Rick Martin of the U.S. Bureau of Reclamation, Pingsheng Chang of the U.S. Geological Survey, Joyce Wolff of Los Alamos National Laboratory and Doug Bausch of Northern Arizona University kindly supplied data from seismic networks in Colorado, New Mexico and Arizona. This research was supported by the U.S. Geological Survey, Department of the Interior, under award numbers 14-08-0001-A0265 and 14-08-0001-G1349, and by the state of Utah.

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ELEMENT D

Communication Systems For Information Transfer

by S. J. Nava, J. Tingey, W. J. Arabasz, A. Popish, and E. McPherson

Emergency management personnel need, the news media expect, and the general public demands, immediate information when a significant earthquake occurs —WJA.

THE AUTHORS

S. J. Nava (Sr. Staff Seismologist), **W. J. Arabasz** (Director), and **E. McPherson** (Electronics Engineer) are all with the University of Utah Seismograph Stations. **J. Tingey** (Earthquake Preparedness Coordinator) and **T. Popish** (Geophysical Engineer) are with the Utah Division of Comprehensive Emergency Management.

Foreword

Earthquake Event Communications, Warning, and Informational Dispersion for Public Safety

Note: This section was provided by Jim Tingey and Tony Popish of the Utah Division of Comprehensive Emergency Management (CEM). We include it here as a foreword because it provides perspective from the emergency management side. A specific proposal and details of a proposed instrumentation plan then follow in expanded form —SJN.

Earthquake information in pre-, early post-, and late post-phases of earthquake emergency management can aid public safety agencies by providing data for decision-making processes, including: early response, resource allocation (location, quantity) and official public statements.

At the present time there are technological and organizational barriers to the efficient dispersion of data to public officials which would be beneficial before or after an earthquake of any "felt" magnitude in Utah. These barriers exist at an inter-state level between agencies and municipalities and at a regional level between the National Earthquake Information Center and CEM. A backup location in Utah for the collection of seismic data does not exist, but may be feasible at the location of the State Emergency Operations Center.

Useful information could be of two types: (1) realtime digital-type data such as magnitude, duration, location, strong motion data; and (2) interpretive data such as modified Mercalli intensity patterns, possible aftershock magnitudes, location patterns, strong motion record interpretations, attenuation over affected areas, and other seismological interpretations of pre- or post- event data. The expertise of seismic professionals combined with their confidence in the instrumented data will be vital to decision-making groups at various levels of government and probably the private sector.

The present communication system used by the Utah Department of Public Safety and the Division of Comprehensive Emergency Management, relies on existing phone services and two basic, statewide radio channels. Past experience in emergency situations and staged exercises have demonstrated that neither system will be adequate for immediate notification or long-term communications operations. Upgrading of the communications system is an on-going project of CEM under our state and federal mandates. The integration of seismic network and interpretive instruments into the standard operating procedures of emergency response will require cooperation between UUSS, Public Safety, CEM, and the Department of Administrative Services (Telecommunications and Data Processing Divisions).

At a minimum, the telecommunications technology which is used by CEM to transmit and receive data from the Federal Emergency Management Agency and Public Safety, should be integrated and implemented by UUSS. This technology utilizes digital packet radios, microwave systems, and pagers for immediate notification. Another tool which is rapidly becoming common is the use of graphic locational data displayed on personal computers. Such systems can be tied into seismic networks and used by public officials in conjunction with interpretations by seismologists and other experts.

A sophisticated notification system is only a natural progression from the present system which requires notification after an event of magnitude 3.0 or greater. If further action is deemed necessary (at this point a very subjective determination), notification is initiated by a simple fan-out procedure.

With the advantage of a shorter notification period, various thresholds of warning and alert could be outlined. The rationale and procedures now used in the Parkfield experiment could be modified to fit conditions in Utah. These levels of alert would be useful in keeping public officials, emergency responders, and in some cases the public informed of the potential threat and the required response level.

Statement of Problem

Emergency management personnel need, the news media expect, and the general public demands, immediate information when a significant earthquake occurs. Existing communications systems in Utah do not provide:

- Reliably continuous earthquake recording
- Immediate alert that a sizable earthquake has occurred
- Adequately rapid determination of event size, location, and hazard assessment
- Rapid transfer of vital information to emergency management personnel and others

Furthermore, these systems are too vulnerable to disruption, and they are too dependent on the availability and intervention of key personnel, taking little to no advantage of existing technology for automated and rapid information transfer.

Specific goals

A. New computer system (prerequisite for other goals).

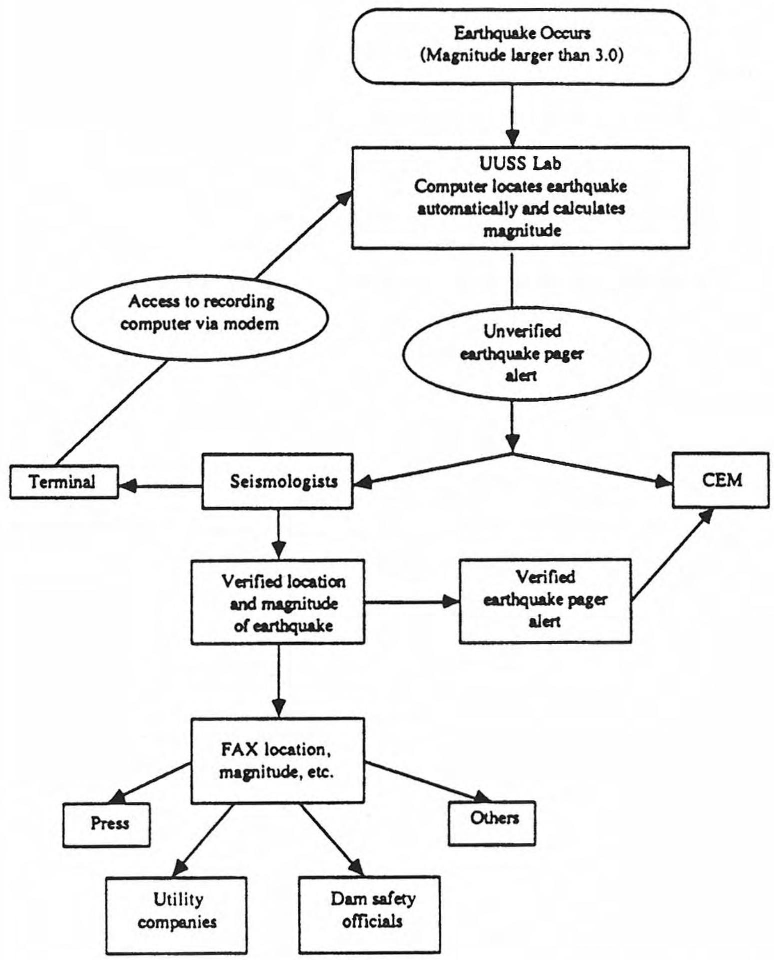
B. Pre-earthquake preparedness, including:

- Ongoing accessibility by emergency management officials to an up-to-date, computerized earthquake data base, supplemented by relevant earthquake information routinely transmitted by seismologists.
- Plan for appropriate emergency management response, given specific seismological input (ideally, with quantified alert stages).
- Redundant scheme for capturing vital earthquake data at new CEM Emergency Operations Center (EOC), and possibly at additional EOC sites in Utah, ensuring rapid access to that data as well as preservation of unique information for science and engineering.

C. Immediate Post-earthquake response (Figure D-1):

- Automated determination of earthquake parameters and automated telephone and/or pager alarm—leading to immediate (near-real-time) notification by computer of earthquake occurrence to seismologists and emergency management personnel.
- Rapid hazard assessment by seismologists of (1) earthquake parameters, (2) the extent of strong ground motion, and (3) estimate of potential damage distribution.
- Effective transfer of information (involving reliable communication systems) to emergency management officials and others who are in a need-to-know capacity (e.g., dam safety officials, utility companies, etc.).

IMMEDIATE POST-EARTHQUAKE RESPONSE



SIGNIFICANT, DAMAGING EARTHQUAKE RESPONSE

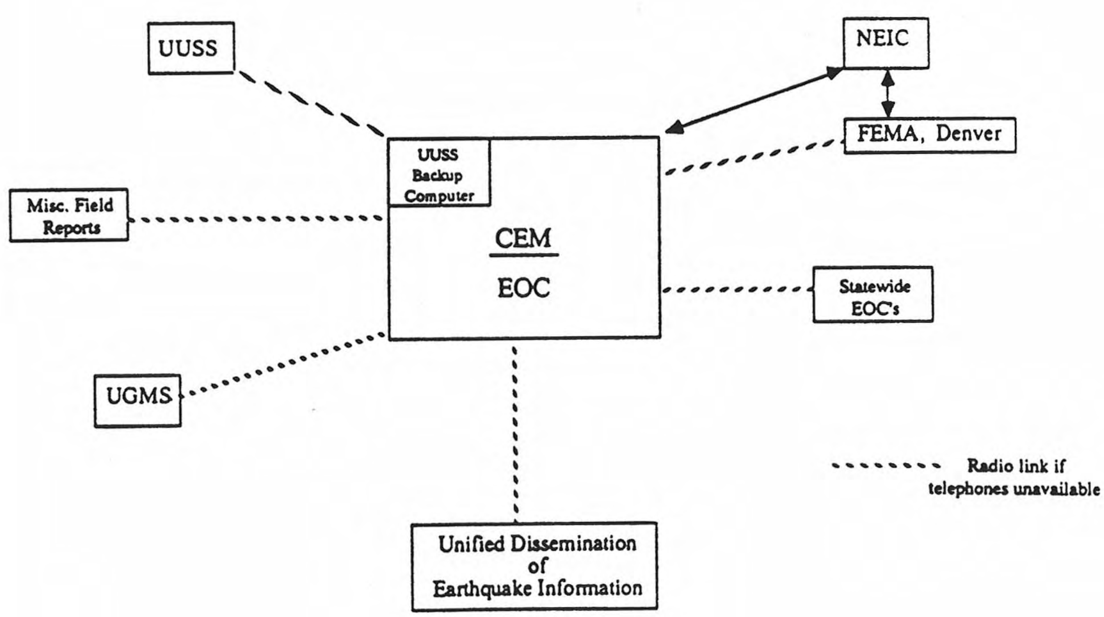


Figure D-1.

Instrumentation Plan for Pre-earthquake Preparedness

- *Online earthquake data base:* We propose to install a system modeled after the Quick Epicenter Determination (QED) of the National Earthquake Information Center. CEM would be able to dial up the UUSS computer system to obtain regular updates on recent earthquake activity as well as have access to the Utah earthquake catalog. This dialup utility could be made available to anyone wishing access to the system. When initiated from CEM headquarters, the data obtained could be plotted on the graphics workstation to be located at their facilities, providing them with a constant snapshot of the seismicity of the state.

- *Routine distribution of earthquake information:* Whenever any significant earthquakes occur, UUSS routinely distributes relevant information to individuals in a need-to-know capacity (CEM, dam safety officials, utility companies, etc). The distribution of this information could be accomplished very efficiently through a FAX network. A FAX-based network would allow rapid dissemination of information to multiple locations, eliminating the need for (1) multiple telephone conversations by seismologists in which the same information is repeated and (2) error-prone dictation of technical information to telephone receptionists.

- *Emergency response plan:* (Note: This item is tangential to instrumentation issues, but represents an important practical goal.) A system of alert stages ideally should be developed to allow seismologists to inform emergency management officials in an orderly way of the possibility of increased earthquake danger. Communications would be delivered in some form linked to probabilistic statements, in a manner similar to that being used in Parkfield, California. Thus, if seismologists observe unusual earthquake activity, for which research has quantified the likelihood of a following significant earthquake, an alert could be issued to CEM. The seismologist would specify the level of the alert, thus allowing CEM to take appropriate action for that level (for example, moving emergency vehicles out of buildings).

- *Redundant earthquake data collection:* We propose to install a scaled-down version of the network recording computer system at CEM headquarters. This backup computer system would be capable of recording 48 channels of earthquake data directly from a pre-existing microwave drop site at the CEM offices. Equipment needed would include a small Masscomp computer with a graphics workstation and the electronics needed to pull the signals off the state microwave system. The backup computer system would be compatible, both in terms of hardware and software, with the computer system chosen for the UUSS central recording facilities.

Instrumentation Plan for Immediate Post-earthquake Response

- *Automated earthquake notification system:* As a supplement to the computer system proposed in Element A, an automatic earthquake notification system will be installed. Computer software would automatically determine the location and size of the earthquake, and if the event were larger than a predetermined magnitude, would initiate automated notification to seismologists. A digital pager broadcast system would be used to notify designated personnel, informing them of the earthquake location and magnitude via an alphanumeric pager display.

  Once notified, the seismologist, using a modem and a terminal, could then dialup the central recording computer, display trace information, and verify the earthquake size and location. After the earthquake had been satisfactorily located, the computer could then initiate pager broadcasting to key emergency management personnel.

  At CEM headquarters, an interactive map could be displayed, depicting the earthquake location and regions of predicted peak horizontal accelerations. As strong motion data were processed by UUSS personnel, observed horizontal accelerations could replace predicted values for emergency management hazard assessment purposes.

- *Reliable communications systems:* After an earthquake, it is vitally important that up-to-date and accurate earthquake information be given to the public, the press, and emergency management personnel. Under the current earthquake response plan, UUSS and UGMS representatives would travel to CEM headquarters (1) to coordinate dissemination of available earthquake information in a unified manner, (2) to provide state leaders with technical information and advice, and if telephone service is disrupted (3) to have access to incoming field reports over emergency radio links and voice communication with NEIC in Golden, Colorado, via a radio link routed through the regional office of the Federal Emergency Management Agency in Denver. We propose the establishment of a secure, direct voice communication link between UUSS, CEM and UGMS, via a UHF radio system. Mobile radios should be installed in 2 UUSS field vehicles to facilitate hazard assessment and coordinated deployment of portable seismographs.

Justification of Instrument Plan

Placing the UUSS backup computer system at the new CEM offices at the State Capitol (expected occupancy - September 1990) would be advantageous to both UUSS and CEM.

- Location of the redundant network recording computer in the CEM Emergency Operations Center would provide a constant emergency power supply for the computer in case of regional power failure.
- UUSS could take advantage of a pre-existing microwave drop point to retrieve earthquake data telemetered over the state microwave system.

- CEM would have access to vital earthquake parameters (magnitude, location and strong ground motion) through the backup computer, allowing CEM to make decisions about emergency response in near-real time.
- The current disaster response plan for a large earthquake in Utah requires that a seismologist be stationed at CEM headquarters. Placement of the backup computer system at CEM headquarters would allow that seismologist to have immediate access to essential earthquake data.

Under the current system, no alarm sounds when an earthquake occurs. Seismologists are generally unaware that a felt earthquake has occurred until contacted, by telephone, by the demanding press, or by concerned citizens. This often results in embarrassment when the earthquake occurs outside of the business day.

- Under the proposed system, seismologists would be alerted—with magnitude and location parameters displayed on alphanumeric pagers—near-real time.
- Using a desktop computer, from home, the seismologist could quickly verify the accuracy of the automatic computerized earthquake location, and alert emergency management personnel with minimal delay.

A relatively expensive mini-computer system (small Masscomp) was chosen over a less expensive desktop computer as the backup computer system for several reasons:

- A desktop computer could serve as a backup recording computer, however such a system would be limited to a small number of incoming data channels (16) vs a mini-computer system capable of processing the 48 channels currently being transmitted on the state microwave system.
- New software would have to be developed if the backup computer was a desktop computer.
- The staff would have a more difficult time processing the data on an operating system different from that in everyday use—especially in times of high pressure, such as after a large earthquake.
- Data formats on a desktop computer would necessarily be different than that of the main recording computer, leading to incompatibility of data sets.

Cost Estimate

A. One-time Costs

†FAX machine for UUSS	$ 2,600
Mobile radio repeater/base station	3,000
†6 hand-held UHF radios (1-CEM, 1-UGMS, 4-UUSS)	4,278
†2 Antennas for UUSS field trucks	800
†11 Digital alphanumeric pagers (4-UUSS, 4-CEM, 2-UGMS, 1-Dam Safety)	3,850
5 Tektronix-compatible color graphics monitors	9,100
5 Modems	2,000
Mini-Masscomp computer system with graphics workstation, capable of recording 48 channels of seismic data	50,000
Electronics needed to interface between mini-Masscomp and state microwave systems for 48 channels (discriminators, instrument rack, cables, connectors, etc.)	8,475
Total One-Time Costs	**$84,103**

B. Recurring Costs

Hardware maintenance (Annual cost estimated to be 10% of the initial cost of the equipment)	6,110
†3 dedicated telephone lines - annual cost	1,368
†Paging Service - annual cost	1,980
Total Recurring Costs	**$ 9,458**

† Exact number to be worked out at a future date.

ELEMENT E

Earthquake Deformation Monitoring from Global Positioning Satellite Measurements

by Charles Meertens and Robert B. Smith

THE AUTHORS

CHUCK MEERTENS, is jointly an Assistant Research Professor at the University of Utah and a Research Associate of the University of Colorado. He has three years' experience with GPS field experiments and data processing. **BOB SMITH** is a Professor of Geophysics at the University of Utah and, among other distinctions, President of the Seismology Section of the American Geophysical Union. Both Meertens and Smith are affiliated with UNAVCO—the University NAVSTAR CONSORTIUM sponsored by the National Science Foundation.

The Problem

The potential for a large earthquake on the Wastatch fault dominates the earthquake threat in Utah. Precise geodetic measurements are being aggressively made in the vicinity of major active faults in other seismically dangerous regions—with the aim of learning about, and hopefully identifying, preseismic ground deformation. Geodetic measurements in Utah, and especially along the Wasatch fault, are urgently needed to establish baseline data for monitoring crustal deformation separate from observed seismicity. The two may not simply be related.

Goal

That the state of Utah acquire three portable GPS receivers for (1) making precise measurements of crustal deformation and (2) serving needs of the state engineering community for surveying and mapping.

The GPS is a . . . satellite-based positioning system . . . (that) allows centimeter level geodesy to be performed with relatively low-cost portable receivers.

What is GPS?

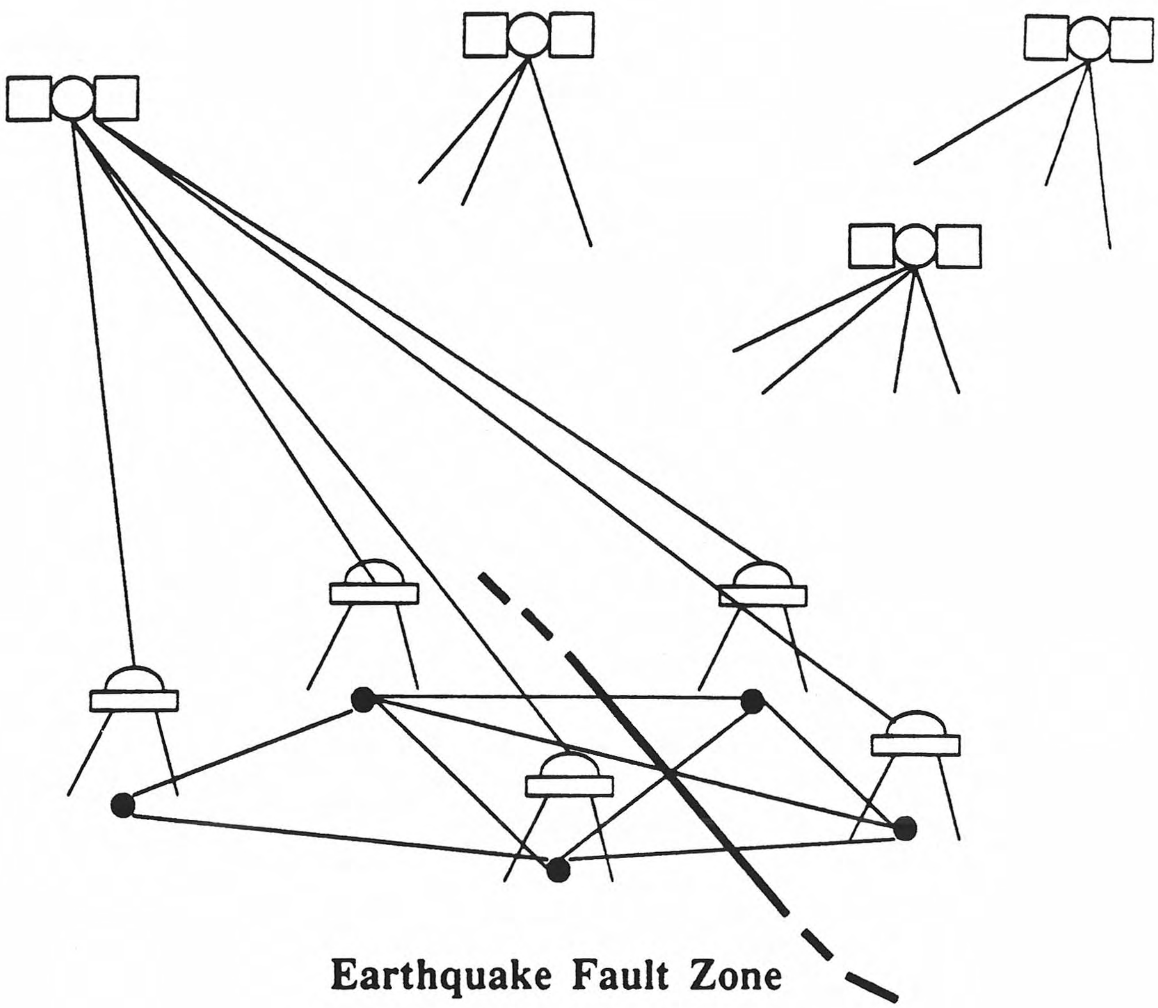
The GPS (Global Positioning System) is a multi-billion dollar satellite-based system developed by the Department of Defense for navigation purposes. When fully implemented, there will be 21 NAVSTAR satellites orbiting the earth providing 24-hour worldwide satellite coverage. GPS allows centimeter level geodesy to be performed with relatively low-cost portable receivers.

Figure E-1 schematically illustrates how multiple satellite signals are simultaneously received at two or more ground stations. Signals from four or more satellites allow an accurate determination of user position and time.

More Background

Measurements of ground deformation around faults are an integral component of earthquake hazard assessments, precursory earthquake monitoring, and engineering studies. Recent developments in GPS satellite technology have provided an effective and affordable means of making high-accuracy crustal deformation measurements. The ground movement associated with processes leading to a major earthquake or large-scale

Crustal Deformation Monitoring with (GPS)



- **Portable receivers record radio signals from orbiting GPS satellites**
- **GPS surveying yields high accuracy horizontal *and* vertical measurements**
- **Repeated surveys used to monitor deformation over 10s of meters to 1000s of kms**
- **Lower cost, faster, and more versatile than conventional geodetic surveys**

Figure E-1.

subsidence following a large event, can affect areas of hundreds of square kilometers with vertical displacements as large as several meters and may occur over a time period of days to years (see Figure E-2). GPS surveying is ideally suited to measure this deformation phenomena and is revolutionizing surveying. To be useful, however, benchmarks must first be established and then planned for systematic resurveying at appropriate intervals.

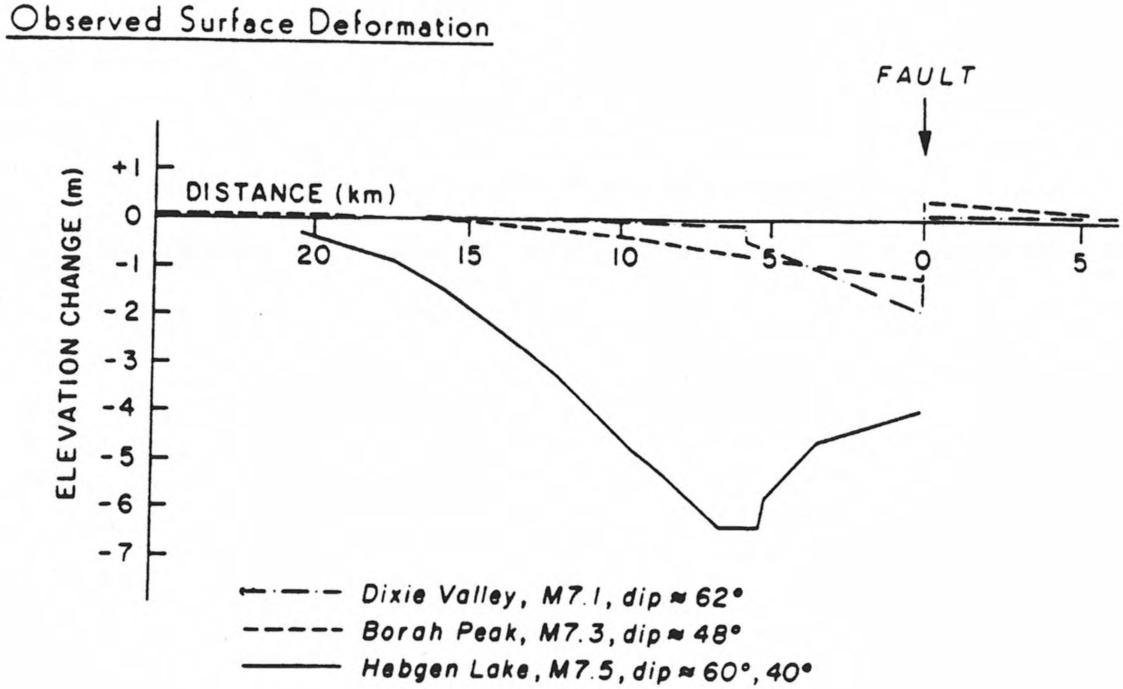
In addition to providing valuable data for earthquake deformation, GPS monitoring is proving to be of great benefit to the engineering community. GPS provides nationwide geographic control points, which are needed for local surveying and mapping. Improved local geographic positions are needed for accurate Geographic Information Systems (GIS) for urban planning, land management, boundary mapping, highway information, and a number of other geographic applications. A number of states (including California, New Mexico, Montana, Tennessee, and Florida) have taken lead roles in working with the National Geodetic Survey and their universities to establish GPS control sites throughout their states. Although the accuracy needs of the engineering surveying community are low (10-1.0 ppm) compared to high accuracies needed to monitor earthquake related crustal deformation (0.1-0.01 ppm), it is important to realize that if managed properly GPS can provide the data for both needs.

GPS Accuracy

The user community has demonstrated that accuracies of millimeters to centimeters can be achieved on baselines ranging from meters to thousands of kilometers. The horizontal accuracy of GPS measurements is as good or better than that of conventional surveying, and the vertical accuracy approaches that of traditional (and expensive) line-leveling. GPS surveys are much less expensive than conventional surveys, do not require line-of-sight between receivers (i.e., you can simultaneously measure points, for example, between Salt Lake City and Provo), and can be made under all weather conditions. With an investment in GPS equipment comparable in cost to that of a conventional surveying station, scientific and engineering surveyors can take advantage of a high-technology system that was established at great expense by the U.S. Government.

GPS in Utah

GPS measurements of crustal deformation in Utah will cover a range of scales. Although the emphasis of this proposal is on seismic hazards, GPS could also be used to monitor deformation associated with loading from changes in level of the Great Salt Lake, with expected land deformation associated with the development of waste repositories, with mining, and so on. The approximate number of benchmarks needed and the frequency of observations will depend on the scale of the problem



Vertical surface deformation caused by three M7+ earthquakes in the Intermountain Seismic Belt and the Basin and Range Province: 1954 M_s7.1 Dixie Valley, Nevada; 1983 M_s7.3 Borah Peak, Idaho (Stein and Barrientos, 1985); and 1959 M_s7.5 Hebgen Lake, Montana (Savage and Hastie, 1966).

Figure E-2.

(Taken from Smith and Richins, 1984, *U.S. Geol. Surv. Open-File Rept. 84-763*, p. 73-112.)

Large-scale Measurements (100-1000 km): The tectonic forces leading to earthquakes in Utah are inherently related to the expansion of the Great Basin, which spans 1,000 km from western Nevada to the Wasatch Front in Utah. Seismicity studies indicate that the Basin-Range has been extending at a rate of 1 cm/year over the last decade, but the details of the deformation are not known. Is the deformation in Utah restricted to zones of active seismicity east of the Wasatch Front? to subsidiary faults? to buried and "blind" faults? or is it associated with the seismically quiescent Wasatch fault? Large scale GPS measurements in Utah can provide much of this detail. Tens to a hundred GPS sites at this scale would have to be surveyed.

Intermediate-scale Measurements (10-100 km): This is the scale of individual fault-bounded blocks and coincidentally is the typical spacing between sites of the state geodetic control networks. Approximately 30-40 GPS sites in Utah would be needed. Sites which would serve primarily as geodetic control sites could be surveyed once and then resurveyed only as the need arises. Sites in areas of greater earthquake risk should be surveyed every 3-5 years.

Small-scale Measurements (0.1-10 km): Station density at this scale is needed to provide details of deformation in the vicinity of individual faults such as individual segments of the Wasatch fault. Here the priority would be given to segments where there is the greatest probability of damaging earthquakes near population centers. In order to resolve the rate of deformation, it would be desirable to have 10's of sites per location resurveyed every 1-2 years. If there are indications of precursory activity in the geodetic or seismic data, more frequent measurements would be necessary.

Lake Inundation from Large Earthquakes

Preliminary studies at the University of Utah show that significant portions of either Salt Lake City, Provo, or Bountiful, could be inundated with up to several meters of water from the Great Salt Lake if an earthquake comparable to the 1959 Hebgen Lake earthquake (our best model for a large earthquake on the Wasatch Front) were to occur along an adjacent segment of the Wasatch fault (see Fig. E-3). Such an event could produce as much as 6 m of valley subsidence. For this work a lower accuracy is needed (only 10s of cm), and kinematic GPS techniques could be used. As opposed to static GPS measurements needed for high accuracy where one receiver sits at one site for a minimum of one 6-hour observation, kinematic surveys require only a few minutes per site and a great number of sites can be surveyed each day.

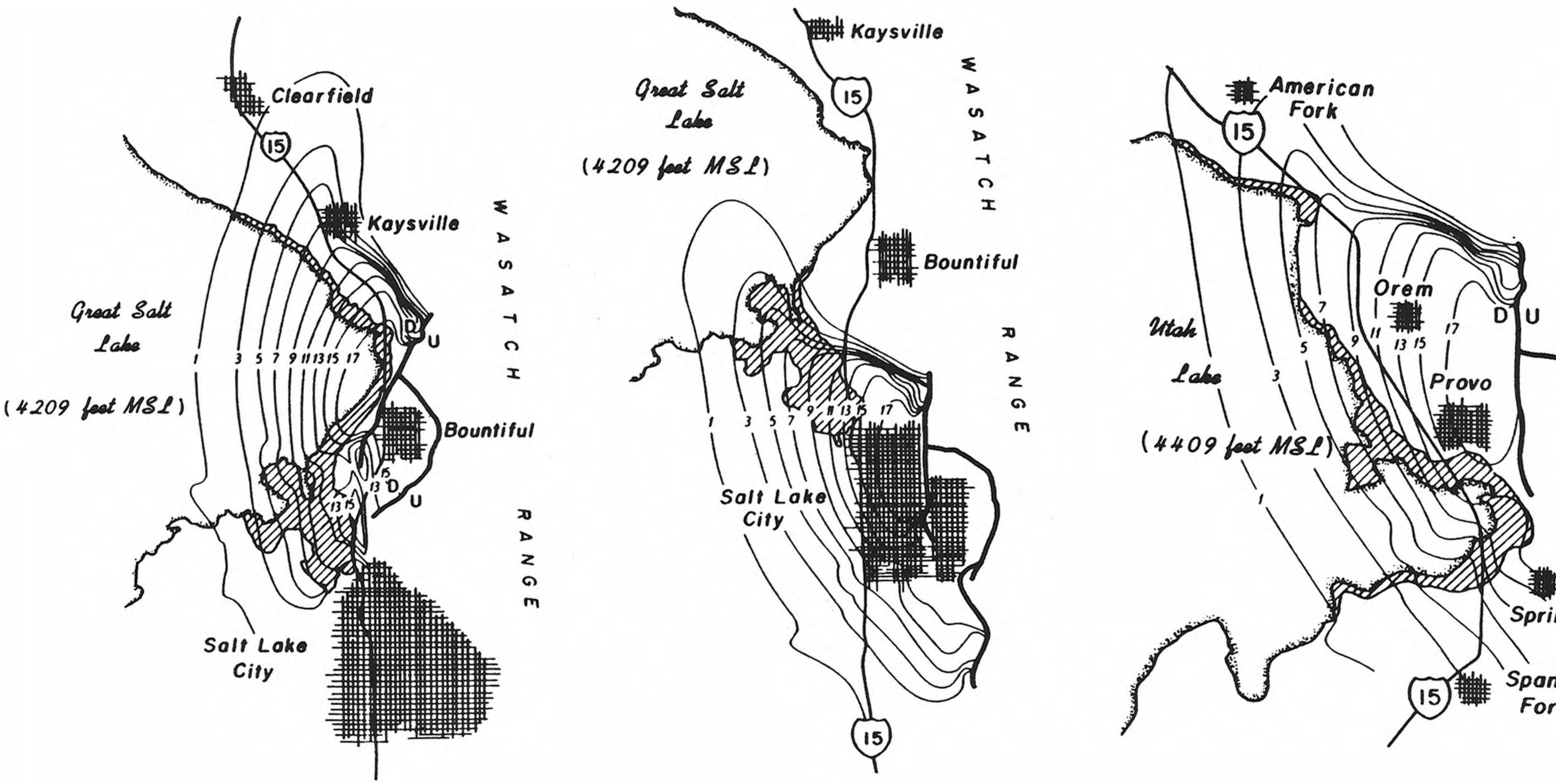


Figure E-3.

Maps of hypothetical flooding (slash pattern) produced by hanging-wall subsidence (i.e., downdropping of the valley block) of the M7.5 Hebgen Lake earthquake for three Wasatch Front locations. Solid line is the location of the Hebgen Lake fault; contours (in feet) correspond to subsidence. (Adapted from Smith and Richins, 1984, *U.S. Geol. Surv. Open-File Rept. 84-763*, p. 73-112.)

Elevation Changes Associated with Other Phenomena

Another application of GPS on a small scale is precise measurements of elevations. This type of mapping can reveal the long-term deformation of the present day topography, such as around the Great Salt Lake and other bodies of water, where the question of land subsidence is related to lake loading and post earthquake deformation. Landslide activity that menaces the Wasatch Front and other steep and slide prone areas can be monitored easily with GPS.

The studies proposed above would, however, clearly be limited to the available people and equipment resources. Initially, a smaller number of sites could be established which would be followed by desification and resurveying as other possible earthquake precursors (such as seismic indicators) are identified or as identifiable inundation zones and earthquake faulting models are assessed. What is clear is that without initial measurements, it will be impossible to recognize changes in crustal deformation patterns that might signal an impending earthquake.

GPS Instrumentation

We suggest that the state of Utah acquire three portable GPS dual-frequency receivers that are priced from $50-60K each. Additional miscellaneous supplies are about $3-5K. The cost of maintenance will depend on the manufacturer.

GPS Experience in Utah

The Department of Geology and Geophysics at the University of Utah has been actively involved in GPS surveying since 1987. Initially, the University of Utah submitted two proposals to the National Science Foundation for GPS work in the Intermountain region: 1) the Wasatch Front, and 2) the volcanically active Yellowstone Park. The Yellowstone project was funded because Yellowstone has much higher earthquake occurrence rates and high uplift rates of centimeters/year associated with a volcanically active caldera.

The University of Utah has since established a high-accuracy GPS 75-station network over the Yellowstone National Park-Teton fault-Hebgen Lake fault region to monitor deformation of the volcanic caldera and surrounding earthquake zones. This work was done under the sponsorship of the National Science Foundation through the University NAVSTAR CONSORTIUM (UNAVCO) and in association with the NGS (National Geodetic Survey), MIT, and the University of Colorado. The success of our project greatly benefited from the cooperative work with these groups. As a member of UNAVCO, the University of Utah has access to technical support and GPS processing software, which can be run on powerful University of Utah computer workstations. Because the data collected will be needed for decades, the NGS archives GPS data and results that meet NGS standards into their database.

Why Should the State of Utah Acquire GPS Instrumentation?

While it could be argued that, in principle, federal or local agencies should fund this type of crustal monitoring work, the fact is that for several reasons the state of Utah will have to take its own initiative.

- Although both the NGS and USGS are involved in making GPS measurements throughout the United States, they do not have the mandate or the resources for all areas of seismic risk. Due to recent budget reductions, much of the fieldwork done by the NGS is funded by the individual states of by other agencies or the federal government. Similarly, the USGS focuses their GPS monitoring primarily on the San Andreas fault.
- Due to the high demand for use of a limited number of GPS receivers available to university groups for scientific work, GPS receivers will not be available in order to respond quickly to areas where other indication show imminent danger of earthquake activity. GPS receivers under control of the state of Utah will ensure that measurements can be made before not after the earthquake occurs.
- Earthquake risk is not confined to counties or cities. It can be anticipated that local surveyors and engineers will also use GPS within their boundaries, but the state must oversee the geodetic deformation monitoring program and coordinate the use of GPS receivers during times of high seismic risk.

A Possible Scenario for a Utah GPS Initiative

To ensure statewide availability for the proposed GPS equipment, the GPS activities should be coordinated by a state agency, perhaps the Utah Geological and Mineral Survey (UGMS) , in cooperation with the University of Utah. To make maximum use of the GPS receivers, GPS surveys and the installation and maintenance of survey instruments would be undertaken by state, county, and city surveyors as well as by scientists of the University of Utah, other universities, and the UGMS. Scientists at the University of Utah would oversee GPS projects that have application to earthquake hazards studies and could process and analyze these data. A managing committee made up of local and national users of GPS could form an oversight and planning group.

. . . the NGS is trying to encourage state participation in geodetic control networks and has a program to provide up to half the salary of a NGS-State geodetic advisor residing in Utah.

It should be noted that some financial assistance will be available from the NGS. This organization is willing to provide technical support for benchmark monumentation, data archiving, and processing software, and coordination with NGS surveys. In addition, the NGS is trying to encourage state participation in geodetic control networks and has a program to *provide up to half the salary* of a NGS-State geodetic advisor residing in Utah. Under current budget constraints, NGS will only be able to make GPS surveys if paid to do so. However, it may be cost effective to hire NGS to help establish the Utah state control network.

Summary

The State of Utah has an opportunity to initiate a statewide multi-agency effort to monitor crustal deformation associated with earthquakes and to assess longterm deformation associated with other land motion unique to Utah. This initiative will compliment the state's earthquake studies, emergency response, and prediction efforts using seismological techniques. Purchase of three GPS receivers will allow detailed measurements along the more high-risk fault zones such as the Wasatch fault. This GPS equipment and University expertise with GPS can also be shared with county and city surveyors who will greatly benefit from this new technology, but who cannot yet afford it. They, in turn, could contribute to surveys and monumentation which are relevant to earthquake monitoring. To ensure with immediate response in times of high earthquake risk and longterm continuity in crustal monitoring, we recommend that a state agency such as the UGMS assume responsibility for maintaining and coordinating the use of the GPS receivers and work under a management committee made up of local and national users of GPS.

UTAH GEOLOGICAL AND MINERAL SURVEY

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THE UTAH GEOLOGICAL AND MINERAL SURVEY is organized into four geologic programs with Administration, Editorial, and Computer Resources providing necessary support to the programs. The ECONOMIC GEOLOGY PROGRAM undertakes studies to identify coal, geothermal, uranium, hydrocarbon, and industrial and metallic mineral resources; to initiate detailed studies of the above resources including mining district and field studies; to develop computerized resource data bases; to answer state, federal, and industry requests for information; and to encourage the prudent development of Utah's geologic resources. The APPLIED GEOLOGY PROGRAM responds to requests from local and state governmental entities for engineering geologic investigations; and identifies, documents, and interprets Utah's geologic hazards. The GEOLOGIC MAPPING PROGRAM maps the bedrock and surficial geology of the state at a regional scale by county and at a more detailed scale by quadrangle. The INFORMATION GEOLOGY PROGRAM answers inquiries from the public and provides information about Utah's geology in a non-technical format.

THE UGMS manages a library which is open to the public and contains many reference works on Utah geology and many unpublished documents on aspects of Utah geology by UGMS staff and others. The UGMS has begun several computer data bases with information on mineral and energy resources, geologic hazards, stratigraphic sections, and bibliographic references. Most files may be viewed by using the UGMS Library. The UGMS also manages a sample library which contains core, cuttings, and soil samples from mineral and petroleum drill holes and engineering geology investigations. Samples may be viewed at the Sample Library or requested as a loan for outside study.

The UGMS publishes the results of its investigations in the form of maps, reports, and compilations of data that are accessible to the public. For information on UGMS publications, contact the UGMS Sales Office, 606 Black Hawk Way, Salt Lake City, UT 84108-1280, telephone (801) 581-6831.