Laboratory Particle Velocity Experiments on Rock
From a USSR Underground Nuclear Test Site

S. A. Miller
A. L. Florence

SRI International
333 Ravenswood Avenue
Menlo Park, CA  94025

February 1990

Scientific Report No. 1

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

GEOPHYSICS LABORATORY
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
HANSCOM AIR FORCE BASE, MASSACHUSETTS  01731-5000
The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Defense Advanced Research Projects Agency or the U.S. Government.

This technical report has been reviewed and is approved for publication.

JAMES F. LEWKOWICZ
Contract Manager
Solid Earth Geophysics Branch
Earth Sciences Division

JAMES F. LEWKOWICZ
Branch Chief
Solid Earth Geophysics Branch
Earth Sciences Division

DONALD H. ECKHARDT, Director
Earth Sciences Division

This report has been reviewed by the ESD Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS).

Qualified requestors may obtain additional copies from the Defense Technical Information Center. All others should apply to the National Technical Information Service.

If your address has changed, or if you wish to be removed from the mailing list, or if the addressee is no longer employed by your organization, please notify GL/IMA, Hanscom AFB, MA 01731-5000. This will assist us in maintaining a current mailing list.

Do not return copies of this report unless contractual obligations or notices on a specific document requires that it be returned.
Particle velocity histories were measured in spherical wave experiments performed in Sierra White granite to test a technique for increasing the useful signal duration for experiments in small diameter cores obtained from the joint verification experiment (JVE) site, and to determine the effects of the pore space condition on wave propagation and attenuation.

The technique used to increase the useful signal duration involved inserting a 6-cm diameter core into a borehole drilled in a 16-cm diameter specimen of the same material. The records from experiments with and without the core/borehole interface showed no effect of this interface. This technique can be used on the 6-cm diameter JVE cores.

Three experiments were performed to compare different initial pore conditions: (1) dry, (2) saturated with equal overburden and pore pressures, and (3) saturated with 11.7 MPa effective stress. The results showed that any effects of initial pore condition are within experimental scatter. Therefore, an initial effective stress is not needed for future experiments, and they will be performed saturated with equal overburden and pore pressures.

These preliminary experiments were performed in preparation for the testing.
program to be completed in the next year of this contract, during which we will perform experiments on rocks from the JVE site and in samples obtained from a potential analog site in Maine.
PREFACE

This research was conducted under Contract F-19628-88-K-0051. Dr. James Lewkowicz was the technical monitor.

The authors are indebted to the following personnel at SRI International for their contributions to this research: E. M. Oyola for preparing and performing the experiments, M. A. Merritt for electronic instrumentation, and D. E. Hutson for machining the specimens.
## CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preface</td>
<td></td>
<td>iii</td>
</tr>
<tr>
<td>List of Illustrations</td>
<td></td>
<td>vi</td>
</tr>
<tr>
<td>1</td>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Experimental Setup</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>2.1 Technique Development</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>2.2 Experiments on the Effects of Pore Fluid</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Experimental Results</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>3.1 Technique Development for Extending Recording Duration</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>3.2 Pore Fluid Effects</td>
<td>13</td>
</tr>
</tbody>
</table>
## LIST OF ILLUSTRATIONS

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Configuration of particle velocity experiments in Sierra White granite to extend useful recording duration of small cores</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>Configuration of particle velocity experiments in Sierra White granite</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>Radial particle velocity histories at a range of 10-mm in Sierra White granite comparing tests with (Test 550) and without (Test 551) an interface</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>Radial particle velocity histories at a range of 15-mm in Sierra White granite comparing tests with (Test 550) and without (Test 551) an interface</td>
<td>9</td>
</tr>
<tr>
<td>5</td>
<td>Radial particle velocity histories at a range of 20-mm in Sierra White granite comparing tests with (Test 550) and without (Test 551) an interface</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>Radial particle velocity histories at a range of 40-mm in Sierra White granite comparing tests with (Test 550) and without (Test 551) an interface</td>
<td>11</td>
</tr>
<tr>
<td>7</td>
<td>Displacement histories in Sierra White granite (Tests 550 and 551)</td>
<td>12</td>
</tr>
<tr>
<td>8</td>
<td>Particle velocity histories for three different pore conditions at 10-mm range in Sierra White granite</td>
<td>14</td>
</tr>
<tr>
<td>9</td>
<td>Particle velocity histories for three different pore conditions at 15-mm range in Sierra White granite</td>
<td>15</td>
</tr>
<tr>
<td>10</td>
<td>Particle velocity histories for three different pore conditions at 20-mm range in Sierra White granite</td>
<td>16</td>
</tr>
<tr>
<td>11</td>
<td>Particle velocity histories for three different pore conditions at 25-mm range in Sierra White granite</td>
<td>17</td>
</tr>
<tr>
<td>12</td>
<td>Particle velocity histories for three different pore conditions at 30-mm range in Sierra White granite</td>
<td>18</td>
</tr>
<tr>
<td>13</td>
<td>Particle velocity histories for three different pore conditions at 40-mm range in Sierra White granite</td>
<td>19</td>
</tr>
<tr>
<td>14</td>
<td>Particle velocity histories for three different pore conditions at 50-mm range in Sierra White granite</td>
<td>20</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>15</td>
<td>Particle velocity histories for three different pore conditions at 65-mm range in Sierra White granite</td>
<td>21</td>
</tr>
<tr>
<td>16</td>
<td>Attenuation of peak velocity for three experiments in Sierra White granite</td>
<td>22</td>
</tr>
<tr>
<td>17</td>
<td>Displacement histories for three different pore conditions at 10-mm range in Sierra White granite</td>
<td>23</td>
</tr>
<tr>
<td>18</td>
<td>Displacement histories for three different pore conditions at 15-mm range in Sierra White granite</td>
<td>24</td>
</tr>
<tr>
<td>19</td>
<td>Displacement histories for three different pore conditions at 20-mm range in Sierra White granite</td>
<td>25</td>
</tr>
<tr>
<td>20</td>
<td>Displacement histories for three different pore conditions at 25-mm range in Sierra White granite</td>
<td>26</td>
</tr>
<tr>
<td>21</td>
<td>Displacement histories for three different pore conditions at 30-mm range in Sierra White granite</td>
<td>27</td>
</tr>
<tr>
<td>22</td>
<td>Displacement histories for three different pore conditions at 40-mm range in Sierra White granite</td>
<td>28</td>
</tr>
<tr>
<td>23</td>
<td>Displacement histories for three different pore conditions at 50-mm range in Sierra White granite</td>
<td>29</td>
</tr>
<tr>
<td>24</td>
<td>Displacement histories for three different pore conditions at 65-mm range in Sierra White granite</td>
<td>30</td>
</tr>
<tr>
<td>25</td>
<td>Attenuation of peak displacement for three experiments in Sierra White granite</td>
<td>31</td>
</tr>
</tbody>
</table>
SECTION 1
INTRODUCTION

The objective of this research project is to support the DARPA program for calibrating the Soviet nuclear test site by generating spherical waves in granite obtained from a borehole drilled adjacent to the site of the joint verification experiment (JVE). At first, our experimental effort focused on the JVE rock; however, this has been modified to include experiments to determine the effects of pore fluid and nonzero effective stress on attenuation and experiments on a suite of rocks obtained from Maine as a possible analog to the JVE rock. We also performed some experiments in technique development to accommodate the small-diameter (6-cm) JVE cores and to extend the duration of measurements before boundary reflections arrive at the measurement positions.

Specifically, our objectives are (1) to determine the effects of pore fluid and effective stress on velocity and displacement attenuation, (2) to generate radial particle velocity histories at different radii from a spherical explosive source in both the JVE rock and rock specimens from Maine and compare the results, (3) to generate strain histories and strain path data from the spherically divergent dynamic loading condition, and (4) to determine if attenuation in hard (low-porosity) rock is independent of the rock constituents (i.e., compare different types of granite, metamorphosed limestone, etc.).

In this report, we present the results of the technique development effort to extend the useful signal duration and the effects of pore fluid and effective stress on wave propagation. Because of the limited number of Maine and JVE specimens, we used Sierra White granite for the technique development and pore fluid effects experiments.

In Section 2, we present the setup for the experiments; the results are in Section 3. During the next year of this contract, we will complete the experiments listed in the test matrix shown in Table 1.
<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Load Condition</th>
<th>$P_{\text{eff}}$ (psi)</th>
<th>Tests</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sierra White granite&lt;sup&gt;a&lt;/sup&gt;</td>
<td>$P_c = 2000$ psi $P_p = 0$</td>
<td>Dry</td>
<td>1</td>
<td>Determine the effect of pore fluid and effective stress on coupling/attenuation of intact hard (low-porosity) rock</td>
</tr>
<tr>
<td></td>
<td>$P_c = 2000$ psi $P_p = 2000$ psi</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$P_c = 2000$ psi $P_p = 0$</td>
<td>2000</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>JVE</td>
<td>$P_c = 2000$ psi $P_p = 1000$-2000 psi</td>
<td>0-1000</td>
<td>2</td>
<td>Measure velocity, displacement, and strain histories/attenuation in JVE rock under divergent loading</td>
</tr>
<tr>
<td>Analog (Maine)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limestone</td>
<td>$P_c = 2000$ psi $P_p = 1000$-2000 psi</td>
<td>0-1000</td>
<td>2</td>
<td>Compare response of three different rock types to determine (1) if coupling and attenuation are comparable to those of JVE rock and the rock is a suitable analog, and (2) if coupling in &quot;hard rock&quot; is independent of rock type</td>
</tr>
<tr>
<td>Coarse-grained granite</td>
<td>$P_c = 2000$ psi $P_p = 1000$-2000 psi</td>
<td>0-1000</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Fine-grained granite</td>
<td>$P_c = 2000$ psi $P_p = 1000$-2000 psi</td>
<td>0-1000</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup>Completed.
SECTION 2
EXPERIMENTAL SETUP

2.1 TECHNIQUE DEVELOPMENT

The specimens obtained from the Soviet test site are available in 6- and 10-cm-diameter cores. For the particle velocity (PV) experiments, 10-cm cores would provide signal durations up to approximately 20 μs before reflections arrived from the specimen boundary, which time is probably suitable for the purposes of the experiment. However, the number of competent 10-cm cores is limited, so 6-cm cores may need to be included in the testing program. For 6-cm cores, the signal duration before the arrival of boundary reflections is insufficient. We therefore developed and tested a technique to extend the useful signal duration by inserting a 6-cm core into a borehole of a larger diameter specimen of similar shock impedance. The objective was to ensure intimate contact between the core and borehole, thereby minimizing (or eliminating) reflections from this interface. We tested interface reflection effects by comparing particle velocity histories in two experiments on dry Sierra White granite; one included a core/borehole interface, and one was performed without an interface.

The experimental configuration is shown in Figure 1. In these experiments, a 3/8-g spherical charge of PETN powder, packed to a density of 1 g/cm³, is detonated at the center of a granite specimen. Concentric copper loops are placed in machined grooves at radii of 1.0, 1.5, 2.0, and 4.0 cm from the center of the charge. Particle velocity is measured by monitoring the induced voltage of the copper loops as they move at the local particle velocity through an externally applied magnetic field. Particle velocity is proportional to the conductor length, the induced voltage, and the magnetic field strength. A hydrostatic overburden pressure of 14 MPa is applied to each specimen.

We prepared the specimens by grinding their faces flat and machining a spherical cavity for the charge and grooves for the particle velocity loops. For the interface effects experiment, the circumference of the 6-cm-diameter core was ground and hand-lapped to produce a close fit into a machined borehole of the surrounding granite. Both the core and borehole were cut at a narrow angle (~1 degree), allowing for intimate contact with a press fit of the core into the borehole.
Figure 1. Configuration of particle velocity experiments in Sierra White granite to extend useful recording duration of small cores.

Test 550 (with interface), Test 551 (without interface).
(a) Side View
(b) Top View
2.2 EXPERIMENTS ON THE EFFECTS OF PORE FLUID

We performed three experiments in Sierra White granite with porosity <1% to compare the response for different pore conditions: (1) dry, (2) saturated with equal overburden and pore pressures of 11.7 MPa, and (3) saturated with 11.7 MPa initial effective stress. The experimental configuration for the dry and saturated case with zero effective stress is shown in Figure 2. In the experiment with nonzero initial effective stress, the pore pressure was isolated from the overburden pressure by surrounding the saturated specimen with a fine wire mesh that acted as a reservoir for the pore fluid. The sample and mesh were then surrounded by an aluminum sleeve around the circumference and end caps on the top and bottom with feed-throughs for water egress. Finally, this assembly was inserted in a rubber jacket and epoxied to the end caps. In these experiments, a 3/8-g charge of PETN powder was detonated at the center of a 16.5-cm-diameter cylinder of granite prepared for testing as previously described. Particle velocity histories were measured at eight radii from the center of the charge using the technique described in Section 2.1.

The specimens were saturated by (1) applying and maintaining a vacuum for 12-24 hours, (2) immersing the specimen in deionized/degassed water, and (3) applying an overburden pressure to the sample with a flatjack while maintaining a vacuum on the flat base of the cylindrical specimen for another 12-24 hours.
Figure 2. Configuration of particle velocity experiments in Sierra White granite to determine effects of pore condition on wave propagation.
SECTION 3
EXPERIMENTAL RESULTS

We uncovered a systematic 22% error in the determination of the magnitude of the magnetic field used in the data reduction procedure for obtaining particle velocity histories. Therefore, the particle velocity and displacement histories in the previously reported data on granite are 22% lower than the actual values. Because the error is constant in all measurements, only the magnitude of the values changes and therefore the overall pulse shape, attenuation rates, and conclusions drawn from the results are not affected. We have corrected the error and applied the compensating 1.22 scale factor to the pertinent data from past experiments in Sierra White granite.

3.1 TECHNIQUE DEVELOPMENT FOR EXTENDING RECORDING DURATION

Two experiments were performed to determine the effects of a core/borehole interface needed to extend the useful recording duration of small-diameter specimens. One experiment (Test 550) included an interface, and these results are compared with those from an experiment (Test 551) without an interface.

The results from Tests 550 and 551 are shown superimposed for each measurement location in Figures 3 through 6, and the displacements obtained by integration of the velocity records for both experiments are shown in Figure 7. In the particle velocity records, estimated arrival time from the core/borehole interface is indicated by "I" and reflections from the specimen boundary are denoted by "R." The gage records cannot be interpreted after reflections arrive from the specimen boundary. The reflection times for the two tests are different because of a 2-cm difference in specimen diameters.

As seen in Figures 3 through 6, the pulse shape, duration, and particle velocity amplitudes (except for the peak) are highly reproducible between the two experiments. In particular, we observed no effect of interface reflections in the experimental records because each feature seen in the specimen with an interface is reproduced in the specimen without an interface. The difference in peak particle velocity amplitude has little effect on the displacements as seen in Figure 7.

The secondary pulse in the particle velocity records at about 7 μs at the first location is probably the result of cavity reverberations. This pulse is propagated from the source
Figure 3. Radial particle velocity histories at a range of 10-mm in Sierra White granite comparing tests with (Test 550) and without (Test 551) an interface.
Figure 4. Radial particle velocity histories at a range of 15-mm in Sierra White granite comparing tests with (Test 550) and without (Test 551) an interface.
Figure 5. Radial particle velocity histories at a range of 20-mm in Sierra White granite comparing tests with (Test 550) and without (Test 551) an interface.
Figure 6. Radial particle velocity histories at a range of 40-mm in Sierra White granite comparing tests with (Test 550) and without (Test 551) an interface.
Figure 7. Displacement histories in Sierra White granite (Tests 550 & 551).
region because it arrives at each subsequent gage with reduced velocity at a later time. We believe the cause of the cavity reverberation is an initial cavity radius about 1 mm larger than the charge radius. In later experiments, the initial cavity radius was reduced to the charge radius to ensure intimate contact between the source and the medium.

3.2 PORE FLUID EFFECTS

The particle velocity records for the dry (Test 564), saturated with zero effective stress (Test 563), and saturated with 11.7 MPa effective stress (Test 565) experiments on Sierra White granite are shown superimposed at each gage location in Figures 8 through 15. The attenuation of peak particle velocity with scaled range is shown in Figure 16. The particle displacements, obtained by temporal integration of the velocity records, are shown superimposed at each gage location in Figures 17 through 24, and attenuation of peak displacement with range is shown in Figure 25. Unfortunately, we did not recover data from gages PV7 and in Test 563 because of a malfunction in the recording equipment. The peak velocity at the 3-cm and 4-cm locations in Test 565 also was not obtained because the oscilloscope used to record the data did not operate properly. Therefore, these data are not included in the velocity attenuation plots, but because they have little effect on the displacements, they are included in the displacement attenuation plots. Cavity diameters were measured at about 1.3 cm.

The data from these experiments on low-porosity (<1%) Sierra White granite indicate that the effects of the pore space condition are negligible and cannot easily be resolved within the scatter of the experimental data. Therefore, the experiments on the JVE and analog rocks will be saturated with zero effective stress, which allows more experiments to be performed because of the less complicated sample preparation scheme.
Figure 8. Particle velocity histories for three different pore conditions at 10-mm range in Sierra White granite.
Test 563 SAT. 11.7 11.7
Test 564 DRY 11.7 0
Test 565 SAT. 11.7 0

Figure 9. Particle velocity histories for three different pore conditions at 15-mm range in Sierra White granite.
<table>
<thead>
<tr>
<th>Test</th>
<th>Condition</th>
<th>$P_c$ (MPa)</th>
<th>$P_p$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 563</td>
<td>SAT.</td>
<td>11.7</td>
<td>11.7</td>
</tr>
<tr>
<td>Test 564</td>
<td>DRY</td>
<td>11.7</td>
<td>0</td>
</tr>
<tr>
<td>Test 565</td>
<td>SAT.</td>
<td>11.7</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 10. Particle velocity histories for three different pore conditions at 20-mm range in Sierra White granite.
Figure 11. Particle velocity histories for three different pore conditions at 25-mm range in Sierra White granite.
Figure 12. Particle velocity histories for three different pore conditions at 30-mm range in Sierra White granite.
Figure 13. Particle velocity histories for three different pore conditions at 40-mm range in Sierra White granite.
Figure 14. Particle velocity histories for three different pore conditions at 50-mm range in Sierra White granite.

<table>
<thead>
<tr>
<th>Test</th>
<th>Pore Condition</th>
<th>P_c  (MPa)</th>
<th>P_p  (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>563</td>
<td>SAT.</td>
<td>11.7</td>
<td>11.7</td>
</tr>
<tr>
<td>564</td>
<td>DRY</td>
<td>11.7</td>
<td>0</td>
</tr>
<tr>
<td>565</td>
<td>SAT.</td>
<td>11.7</td>
<td>0</td>
</tr>
</tbody>
</table>
Figure 15. Particle velocity histories for three different pore conditions at 65-mm range in Sierra White granite.
\[ \hat{u}(\hat{r}) = 3714(\hat{r})^{-1.23} \]

Where \( \hat{r} = \text{Scaled Range} \)

### Table 1

<table>
<thead>
<tr>
<th>Core Condition</th>
<th>( P_c ) (MPa)</th>
<th>( P_p ) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 563 SAT.</td>
<td>11.7</td>
<td>11.7</td>
</tr>
<tr>
<td>Test 564 DRY.</td>
<td>11.7</td>
<td>0.0</td>
</tr>
<tr>
<td>Test 565 SAT.</td>
<td>11.7</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Figure 16. Attenuation of peak velocity for three different core conditions in Sierra White granite.
Figure 17. Displacement histories for three different pore conditions at 10-mm range in Sierra White granite.
Figure 18. Displacement histories for three different pore conditions at 15-mm range in Sierra White granite.
Figure 19. Displacement histories for three different pore conditions at 20-mm range in Sierra White granite.
Figure 20. Displacement histories for three different pore conditions at 25-mm range in Sierra White granite.
Figure 21. Displacement histories for three different pore conditions at 30-mm range in Sierra White granite.
Figure 22. Displacement histories for three different pore conditions at 40-mm range in Sierra White granite.
Figure 23. Displacement histories for three different pore conditions at 50-mm range in Sierra White granite.
Figure 24. Displacement histories for three different pore conditions at 65-mm range in Sierra White granite.
Figure 25. Attenuation of peak displacement for three different core conditions in Sierra White granite.

\[ \hat{\mu}(\hat{r}) = 3785(\hat{r})^{-1.15} \]

Where \( \hat{r} \) = Scaled Range
Prof. Thomas Ahrens  
Seismological Lab, 252-21  
Division of Geological & Planetary Sciences  
California Institute of Technology  
Pasadena, CA 91125

Prof. Charles B. Archambeau  
CIRES  
University of Colorado  
Boulder, CO 80309

Prof. Muawia Barazangi  
Institute for the Study of the Continent  
Cornell University  
Ithaca, NY 14853

Dr. Douglas R. Baumgardt  
ENSCO, Inc.  
5400 Port Royal Road  
Springfield, VA 22151-2388

Prof. Jonathan Berger  
IGPP, A-025  
Scripps Institution of Oceanography  
University of California, San Diego  
La Jolla, CA 92093

Dr. Lawrence J. Burdick  
Woodward-Clyde Consultants  
566 El Dorado Street  
Pasadena, CA 91109-3245

Dr. Karl Coyner  
New England Research, Inc.  
76 Olcott Drive  
White River Junction, VT 05001

Prof. Vernon F. Cormier  
Department of Geology & Geophysics  
U-45, Room 207  
The University of Connecticut  
Storrs, CT 06268

Professor Anton W. Dainty  
Earth Resources Laboratory  
Massachusetts Institute of Technology  
42 Carleton Street  
Cambridge, MA 02142

Prof. Steven Day  
Department of Geological Sciences  
San Diego State University  
San Diego, CA 92182

Dr. Zoltan A. Der  
ENSCO, Inc.  
5400 Port Royal Road  
Springfield, VA 22151-2388

Prof. John Ferguson  
Center for Lithospheric Studies  
The University of Texas at Dallas  
P.O. Box 830688  
Richardson, TX 75083-0688

Prof. Stanley Flatte  
Applied Sciences Building  
University of California  
Santa Cruz, CA 95064

Dr. Alexander Florence  
SRI International  
333 Ravenswood Avenue  
Menlo Park, CA 94025-3493

Prof. Henry L. Gray  
Vice Provost and Dean  
Department of Statistical Sciences  
Southern Methodist University  
Dallas, TX 75275

Dr. Indra Gupta  
Teledyne Geotech  
314 Montgomery Street  
Alexandria, VA 22314

Prof. David G. Harkrider  
Seismological Laboratory  
Division of Geological & Planetary Sciences  
California Institute of Technology  
Pasadena, CA 91125

Prof. Donald V. Helmberger  
Seismological Laboratory  
Division of Geological & Planetary Sciences  
California Institute of Technology  
Pasadena, CA 91125

Prof. Eugene Herrin  
Institute for the Study of Earth and Man  
Geophysical Laboratory  
Southern Methodist University  
Dallas, TX 75275

Prof. Robert B. Herrmann  
Department of Earth & Atmospheric Sciences  
St. Louis University  
St. Louis, MO 63156
Dr. Monem Abdel-Gawad  
Rockwell International Science Center  
1049 Camino Dos Rios  
Thousand Oaks, CA  91360

Dr. G.A. Bollinger  
Department of Geological Sciences  
Virginia Polytechnic Institute  
21044 Derring Hall  
Blacksburg, VA  24061

Prof. Keiiti Aki  
Center for Earth Sciences  
University of Southern California  
University Park  
Los Angeles, CA  90089-0741

Dr. Stephen Bratt  
Science Applications Int'l Corp.  
10210 Campus Point Drive  
San Diego, CA  92121

Prof. Shelton S. Alexander  
Geosciences Department  
403 Deike Building  
The Pennsylvania State University  
University Park, PA  16802

Michael Browne  
Teledyne Geotech  
3401 Shiloh Road  
Garland, TX  75041

Dr. Kenneth Anderson  
BBNSTC  
Mail Stop 14/1B  
Cambridge, MA  02238

Mr. Roy Burger  
1221 Serry Road  
Schenectady, NY  12309

Dr. Ralph Archuleta  
Department of Geological Sciences  
University of California at Santa Barbara  
Santa Barbara, CA  93102

Dr. Robert Burridge  
Schlumberger-Doll Research Center  
Old Quarry Road  
Ridgefield, CT  06877

Dr. Thomas C. Bache, Jr.  
Science Applications Int'l Corp.  
10210 Campus Point Drive  
San Diego, CA  92121 (2 copies)

Dr. Jerry Carter  
Rondout Associates  
P.O. Box 224  
Stone Ridge, NY  12484

J. Barker  
Department of Geological Sciences  
State University of New York  
at Binghamton  
Vestal, NY  13901

Dr. W. Winston Chan  
Teledyne Geotech  
314 Montgomery Street  
Alexandria, VA  22314-1581

Dr. T.J. Bennett  
S-CUBED  
A Division of Maxwell Laboratory  
11800 Sunrise Valley Drive, Suite 1212  
Reston, VA  22091

Dr. Theodore Cherry  
Science Horizons, Inc.  
710 Encinitas Blvd., Suite 200  
Encinitas, CA  92024 (2 copies)

Mr. William J. Best  
907 Westwood Drive  
Vienna, VA  22180

Prof. Jon F. Claerbout  
Department of Geophysics  
Stanford University  
Stanford, CA  94305

Dr. N. Biswas  
Geophysical Institute  
University of Alaska  
Fairbanks, AK  99701

Prof. Robert W. Clayton  
Seismological Laboratory  
Division of Geological & Planetary Sciences  
California Institute of Technology  
Pasadena, CA  91125
<table>
<thead>
<tr>
<th>Name</th>
<th>Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr. Ralph Alewine III</td>
<td>DARPA/NMRO 1400 Wilson Boulevard Arlington, VA 22209-2308</td>
</tr>
<tr>
<td>Paul Johnson</td>
<td>ESS-4, Mail Stop J979 Los Alamos National Laboratory Los Alamos, NM 87545</td>
</tr>
<tr>
<td>Mr. James C. Battis</td>
<td>GL/LWH Hanscom AFB, MA 01731-5000</td>
</tr>
<tr>
<td>Janet Johnston</td>
<td>GL/LWH Hanscom AFB, MA 01731-5000</td>
</tr>
<tr>
<td>Dr. Robert Blandford</td>
<td>DARPA/NMRO 1400 Wilson Boulevard Arlington, VA 22209-2308</td>
</tr>
<tr>
<td>Dr. Katharine Kadinsky-Cade</td>
<td>GL/LWH Hanscom AFB, MA 01731-5000</td>
</tr>
<tr>
<td>Eric Chael</td>
<td>Division 9241 Sandia Laboratory Albuquerque, NM 87185</td>
</tr>
<tr>
<td>Ms. Ann Kerr</td>
<td>IGPP, A-025 Scripps Institute of Oceanography University of California, San Diego La Jolla, CA 92093</td>
</tr>
<tr>
<td>Dr. John J. Cipar</td>
<td>GL/LWH Hanscom AFB, MA 01731-5000</td>
</tr>
<tr>
<td>Dr. Max Koontz</td>
<td>US Dept of Energy/DP 5 Forrestal Building 1000 Independence Avenue Washington, DC 20585</td>
</tr>
<tr>
<td>Mr. Jeff Duncan</td>
<td>Office of Congressman Markey 2133 Rayburn House Bldg. Washington, DC 20515</td>
</tr>
<tr>
<td>Dr. W.H.K. Lee</td>
<td>Office of Earthquakes, Volcanoes, &amp; Engineering 345 Middlefield Road Menlo Park, CA 94025</td>
</tr>
<tr>
<td>Dr. Jack Everden</td>
<td>USGS - Earthquake Studies 345 Middlefield Road Menlo Park, CA 94025</td>
</tr>
<tr>
<td>Dr. William Leith</td>
<td>U.S. Geological Survey Mail Stop 928 Reston, VA 22092</td>
</tr>
<tr>
<td>Art Frankel</td>
<td>USGS 922 National Center Reston, VA 22092</td>
</tr>
<tr>
<td>Dr. Richard Lewis</td>
<td>Director, Earthquake Engineering &amp; Geophysics U.S. Army Corps of Engineers Box 631 Vicksburg, MS 39180</td>
</tr>
<tr>
<td>Dr. T. Hanks</td>
<td>USGS Natl Earthquake Research Center 345 Middlefield Road Menlo Park, CA 94025</td>
</tr>
<tr>
<td>James F. Lewkowicz</td>
<td>GL/LWH Hanscom AFB, MA 01731-5000</td>
</tr>
<tr>
<td>Dr. James Hannon</td>
<td>Lawrence Livermore Nat'l Laboratory P.O. Box 808 Livermore, CA 94550</td>
</tr>
<tr>
<td>Mr. Alfred Lieberman</td>
<td>ACDA/VI-OA State Department Bldg Room 5726 320 - 21st Street, NW Washington, DC 20451</td>
</tr>
</tbody>
</table>
CONTRACTORS (Foreign)

Dr. Ramon Cabre, S.J.
Observatorio San Calixto
Casilla 5939
La Paz, Bolivia

Prof. Hans-Peter Harjes
Institute for Geophysik
Ruhr University/Bochum
P.O. Box 102148
4630 Bochum 1, FRG

Prof. Eystein Husebye
NTNF/NORSAR
P.O. Box 51
N-2007 Kjeller, NORWAY

Prof. Brian L.N. Kennett
Research School of Earth Sciences
Institute of Advanced Studies
G.P.O. Box 4
Canberra 2601, AUSTRALIA

Dr. Bernard Massinon
Societe Radiomana
27 rue Claude Bernard
75005 Paris, FRANCE (2 Copies)

Dr. Pierre Mecheler
Societe Radiomana
27 rue Claude Bernard
75005 Paris, FRANCE

Dr. Svein Mykkeltveit
NTNF/NORSAR
P.O. Box 51
N-2007 Kjeller, NORWAY
Dr. Peter Basham  
Earth Physics Branch  
Geological Survey of Canada  
1 Observatory Crescent  
Ottawa, Ontario, CANADA K1A 0Y3

Dr. Fekadu Kebede  
Seismological Section  
Box 12019  
S-750 Uppsala, SWEDEN

Dr. Eduard Berg  
Institute of Geophysics  
University of Hawaii  
Honolulu, HI 96822

Dr. Tormod Kvaerna  
NTNF/NORSAR  
P.O. Box 51  
N-2007 Kjeller, NORWAY

Dr. Michel Bouchon  
I.R.I.G.M.-B.P. 68  
38402 St. Martin D’Heres  
Cedex, FRANCE

Dr. Peter Marshall  
Procurement Executive  
Ministry of Defense  
Blacknest, Brimpton  
Reading RG7-4RS, UNITED KINGDOM

Dr. Hilmar Bungum  
NTNF/NORSAR  
P.O. Box 51  
N-2007 Kjeller, NORWAY

Prof. Ari Ben-Menahem  
Department of Applied Mathematics  
Weizman Institute of Science  
Rehovot, ISRAEL 951729

Dr. Michel Campillo  
Observatoire de Grenoble  
I.R.I.G.M.-B.P. 53  
38041 Grenoble, FRANCE

Dr. Robert North  
Geophysics Division  
Geological Survey of Canada  
1 Observatory Crescent  
Ottawa, Ontario, CANADA K1A 0Y3

Dr. Kin Yip Chun  
Geophysics Division  
Physics Department  
University of Toronto  
Ontario, CANADA M5S 1A7

Dr. Frode Ringdal  
NTNF/NORSAR  
P.O. Box 51  
N-2007 Kjeller, NORWAY

Dr. Alan Douglas  
Ministry of Defense  
Blacknest, Brimpton  
Reading RG7-4RS, UNITED KINGDOM

Dr. Jorg Schlittenhardt  
Postfach 510153  
D-3000 Hannover 51, FEDERAL REPUBLIC OF GERMANY

Dr. Roger Hansen  
NTNF/NORSAR  
P.O. Box 51  
N-2007 Kjeller, NORWAY

Dr. Manfred Henger  
Postfach 510153  
D-3000 Hannover 51, FRG

Ms. Eva Johannisson  
Senior Research Officer  
National Defense Research Inst.  
P.O. Box 27322  
S-102 54 Stockholm, SWEDEN