Project Director: L. T. Long
Sponsor: U. S. Army Engineer District, Savannah
Corps of Engineers, Savannah, GA

Type Agreement: P.O. DACW21-86-M-0136

Award Period: From 2/1/85 To 10/15/85 (Performance) 2/28/86 (Reports)

Sponsor Amount:
Estimated: $
Funded: $

Cost Sharing Amount: None
Cost Sharing No: N/A

Title: Microseismic Data

ADMINISTRATIVE DATA

1) Sponsor Technical Contact: U.S. Army Corps of Engineers
For: EN-BC (Bill Lynch)
P.O. Box 889
Savannah, GA 31402-0889

2) Sponsor Admin/Contractual Matters: S. Godbee
U. S. Army Engineer District, Savannah
Corps of Engineers
P.O. Box 889
Savannah, GA 31402-0889

Defense Priority Rating: None Shown
Military Security Classification: Unclassified
(or) Company/Industrial Proprietary: N/A

RESTRICTIONS

See Attached Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval — Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with none proposed or anticipated

COMMENTS:
Follow-on to G-35-622

SPONSOR'S I. D. NO. 02.102.026.85.001
SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Project No. G-35-636

School/DO Geo. Sci.

Includes Subproject No.(s) N/A

Project Director(s) L. T. Long

Sponsor U.S. Army Engineer District

Title Microseismic Data

Effective Completion Date: 10/15/85

Grant/Contract Closeout Actions Remaining:

- [ ] None
- [X] Final Invoice or Final Fiscal Report
- [ ] Closing Documents
- [X] Final Report of Inventions
- [X] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other

Continues Project No. G-35-622

Continued by Project No. 

COPIES TO:
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ANNUAL REPORT NO. 6
PROJECT NO. G-35-622

MICROEARTHQUAKE INSTRUMENTATION
AND ANALYSIS BETWEEN HARTWELL AND
CLARK HILL RESERVOIR AREAS


By
Dr. Leland Timothy Long
Professor of Geophysics
and
Andreas Georgiopoulos
Graduate Research Assistant

Prepared for
U. S. ARMY CORPS OF ENGINEERS
Savannah District
P.O. Box 889
Savannah, Georgia 31402

Issued April 1986

GEORGIA INSTITUTE OF TECHNOLOGY
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF GEOPHYSICAL SCIENCES
ATLANTA, GEORGIA 30332
ANNUAL REPORT NO. 6

MICROEARTHQUAKE INSTRUMENTATION AND ANALYSIS
BETWEEN HARTWELL AND CLARK HILL RESERVOIR AREAS

Project No. G-35-622

Annual Technical Report for Period
1 January 1985 - 31 December 1985

Prepared By

Dr. Leland Timothy Long
Professor of Geophysics

and

Andreas Georgiopoulos
Graduate Research Assistant

Prepared for

U.S. Army Corps of Engineers, Savannah District
P. O. Box 889, Savannah, Georgia 31402

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GEORGIA INSTITUTE OF TECHNOLOGY
School of Geophysical Sciences
Atlanta, Georgia 30332
INTRODUCTION

The Richard B. Russell Lake now covers the Savannah River valley in the Piedmont Province of Georgia and South Carolina from the headwaters of the Clark Hill Reservoir north to Hartwell Dam. Impoundment of the Savannah River was initiated in December 1983. While most reservoirs do not trigger microearthquakes when they are first impounded, felt and recorded earthquakes near some reservoirs in the Piedmont Province of South Carolina and Georgia show that they have induced seismic activity. The objective of the microearthquake instrumentation and the analysis of data on events occurring between the Hartwell and Clark Hill Reservoirs Areas is to document the seismicity prior to, during, and after impoundment of the Richard B. Russell Lake. Our studies detected no seismic activity in the area before the impoundment of the Richard B. Russell Lake. After the impoundment only low-level, minor seismicity was observed. This report covers the maintenance of the seismic monitoring system from 1 January 1985 to 31 December 1985.

SEISMICITY

The earthquakes observed in the Piedmont Province (Figure 1) occur at scattered locations with little apparent correlation with major geologic structures. Where reliable estimates of their depth are available, the implied depths are shallow and are typically less than two kilometers deep. The largest, the Union County earthquake of 1913, was, perhaps, a magnitude 5.5. The rate of activity is low, with an average of one event greater than magnitude 3.5 occurring less than once every four years in South Carolina and Georgia. Today, the seismicity at magnitudes less than 2.0 is difficult to assess because the shallow focus earthquakes typical of the Piedmont Province generate signatures similar to the signatures of industrial explosions in the many quarries which mine the near-surface crystalline rocks. The seismic monitoring system detects earthquakes or blasts of magnitude zero or less. Hence, an initial objective of the analysis of seismic monitoring data between the Hartwell and Clark Hill Reservoir Areas was to identify the active quarries and other industrial blast sites in order to properly assess the background level of seismicity.

No evidence was found for historical seismicity in the Richard B. Russell Lake area, although the area experienced disturbances from more distant events, such as the 1886 Charleston earthquake and the Clark Hill vicinity earthquakes. The closest epicenters based on currently available data were near Due West and McCormick, South Carolina. Due West is approximately 40 km east of the Savannah River and experienced
Figure 1. Seismicity of the Southeastern United States and its relation to the proposed Richard B. Russell (RBR) Lake. After Bollinger (1973).
earthquakes in 1929, 1930, 1931, and 1956. An earthquake occurred near McCormick on August 2, 1974. On November 1, 1875, a maximum intensity VI (mm) earthquake was noted in the Clark Hill Reservoir Area near Lincolnton, Georgia. These two events occurred 10 to 20 km south of the Richard B. Russell Dam site.

Many of the recent earthquakes in the Piedmont Province have epicenters near reservoirs. These include the Seneca earthquake on July 13, 1971; the Jocassee earthquakes of 1975, 1976, and 1979; and the August 2, 1974, McCormick earthquake. Monticello Reservoir north of Columbia, South Carolina, triggered an extensive sequence of small (magnitude 2.5 to 3.0) earthquakes. Lake Sinclair, Georgia, has exhibited a continuous sequence of events, although the reservoir was impounded in the 1950's and the association with the reservoir is tenuous. Lake Oconee, impounded in the spring of 1979, generated only a short sequence of small (less than M = 0) events in the spring of 1980. The Oconee Reservoir events would not have been noted without a sensitive seismic net. Hence, one can speculate that other reservoirs similarly triggered events, but these events were undetected. In the case of Monticello and Oconee, seismic monitoring was available prior to loading and no significant seismic activity was detected in the vicinity of the forthcoming reservoirs. While at present the pre-impoundment seismicity does not allow predictions of induced earthquakes, it can provide valuable data concerning the occurrence of natural seismic activity.

The Richard B. Russell Lake now covers a 130-km area of the Piedmont Province, an area in which nearby reservoirs are associated with induced seismic activity. Hence, the probability is high that Richard B. Russell Lake may induce some seismic activity. If seismic activity is induced near the Richard B. Russell Lake, the earthquakes will most likely be small, generally felt, and less than magnitude 2.5. Earthquakes with magnitudes as large as 3.5 are not common near Piedmont Province reservoirs (only two events with magnitudes greater than 3.2 occurred at Jocassee) and magnitudes larger than 4.5 are highly unlikely. Earthquakes could conceivably be induced anywhere near the reservoir. An objective of the seismic monitoring is to locate sites of activity should they develop after impounding the reservoir. Because their depths are expected to be shallow, perhaps as shallow as 0.5 to 1.5 km, the widely spaced net cannot determine accurate depths of focus. Instead, portable equipment would be deployed with appropriate spacing to compute depths of focus for events in selected active areas.

SEISMIC NET

The Richard B. Russell seismic net consists of four vertical-component short-period seismic systems. The four stations (see Figure 2) form a network which is elongated in the north-south direction. The four stations are furnished and maintained by the Savannah District Corps of Engineers. Maintenance of the microearthquake monitoring system is provided through the mutual support of Georgia Tech and the Savannah
Figure 2. Location map for the four-station Richard B. Russell Lake Seismic Net.
District Corps of Engineers. Georgia Tech and the Savannah District Corps of Engineers also agree to the mutual use of the microearthquake monitoring system in the area between Hartwell and Clark Hill Reservoirs. Use of the data is confined to non-profit research. Requests for the usage of the data can be submitted directly to Georgia Tech. However, Georgia Tech must forward all requests to the Savannah District Corps of Engineers for approval. A brief report describing the data usage, the seismic events, and copies of the appropriate events shall be submitted to the Savannah District Corps of Engineers.

The designation for the northernmost station is IVA because it is 8 km west-southwest of Iva, South Carolina. IVA is within 1.0 km of the Savannah River and 13 km southeast of Hartwell Lake. Station LDV is 8 km south-southwest of Lowndesville, South Carolina, and 15 km northwest of the Richard B. Russell Dam site, at the headwaters of Clark Hill Reservoir. Station BEV is near the former town of Beverly, Georgia, and 14 km west-northwest of the dam site. Station CHF is south of the town of Calhoun Falls, Georgia, and just east of the Richard B. Russell Dam site. Beginning in October 1985 the data from the field sites were radio-telemetered to station CH6 in the Clark Hill Reservoir Area.

The regional distribution of seismic stations is shown in Figure 3. Station CHF was originally funded by the Savannah District Corps of Engineers and eventually installed by the U.S. Geological Survey. The station originally consisted of one vertical and one horizontal short-period seismometer. The data were telemetered to Columbia, South Carolina, where they were recorded on a helical recorder. Station CHF did not operate during 1983. Reinstallation as a short period vertical component was completed in January 1984 as a part of the Richard B. Russell seismic network. Station PRM on Parsons Mountain is part of the South Carolina Seismic Net operated by the U.S. Geological Survey. Stations EP1, CH5, and CH6 in the Clark Hill area are operated by Georgia Tech with the support of the Nuclear Regulatory Commission. At Georgia Tech, the Clark Hill stations are combined with the three Richard B. Russell stations to form a 75-km linear array. Additional seismic coverage to the north is provided by station SMT operated by Duke Power and the University of South Carolina. To the south, the Savannah River Plant operates a three-station array. To the southeast, station MTT, operated by the U.S. Geological Survey, is part of the South Carolina Net.

INSTRUMENTATION

Components for the microearthquake monitoring system were provided by the Savannah District Corps of Engineers. The system was assembled and installed by Georgia Tech. The specifications and construction of the system were made uniform in order to provide uniform response characteristics.
Figure 3. Locations of seismic stations along the Savannah River.
A vault was constructed to house the instruments in the field. The vault was designed to provide a 10- to 20-cm-thick cement base on which to rest the geophone. Sites were chosen to allow placement of the cement pad as close to bedrock as possible, and on a sufficient slope to guarantee drainage. Cinder blocks were used to build the walls, and the top was covered by a welded iron cover. The design provides for both drainage of water and circulation of air. The instruments are housed in separate weather-proof containers for their protection.

In 1983 radio frequency transmission to the radio tower at the Richard B. Russell Dam was installed in order to minimize phone line costs and lightning damage related to the connection of the equipment to the phone line. At the microwave tower the three RF transmitted signals are mixed with station CHF and transmitted to Georgia Tech via commercial telephone lines. At Georgia Tech, the telephone line signal is conditioned for proper impedance matching for the discriminators. The discriminator bank is designed for plug-in expansion from the existing three to seven possible stations. A patch cord system is used to route the discriminated signals to helical recorders. The timing system for the network is provided by means of a digital timing system at Georgia Tech and provides second, minute, hour, and twenty-four-hour marks for the ink recorders. In the future we expect to drop one station and converge one station to three-component recording.

DATA ANALYSIS

The objective of the data analysis was to review all records obtained from the microearthquake recording system and to compute locations and magnitudes for earthquakes recorded by the system. Seismic activity occurring within the immediate vicinity of the reservoir, as defined by a 50-km radius from the Savannah River, was reported to the Savannah District Corps of Engineers. Discrimination of earthquakes from local quarry blasts or construction explosions requires, in addition, that the principal active quarries be located and identified. In order to simplify the task of identifying quarry blasts and construction explosions, a catalog of common blasts as recorded at each station was developed. Through the use of this chart, a higher percentage of previously located blasts can be identified without requiring the careful measurement of phases for a computer location. This means also that a seismic event is less likely to be mistaken for a blast. Figure 4 identifies the area of investigation and the currently identified sites of explosion as well as the locations of the epicenters of the events that have been detected in the period from 1 January 1985 through April 1986.
Figure 4. Area of investigation, locations of quarries active during the first period of operation of the Seismic Net, and locations of the epicenters of suspected induced events.
COVERAGE

The data analysis presented in this report covers the time period from January 1985 to 31 December 1985. The average percent coverage over the twelve-month period was 89% for at least one station, 83% for two stations, 56% for three stations, and 23% for four stations. Table 1 gives a detailed monthly breakdown of coverage.

REGIONAL SEISMICITY

During the course of the year, several regional seismic events were detected by the stations IVA, BEV, LDV, and CHF. This is a good indication that the above stations are indeed picking up seismic events of a nature other than blasts and that they are functioning properly. A catalog indicating the character and specifics of the regional events can be found on pages 30-36.

SUSPECTED INDUCED SEISMICITY

Three events of suspected natural origin have been detected in the defined area of the Richard B. Russell Seismic Network. These events were detected on 29 January 1985, 27 October 1985, and 13 December 1985. The epicenters are near Danburg, Antreville, and Calhoun Falls (Figures 4, 5a, 5b). Although the seismicity was very low last year as well as the previous years, within the first four months of 1986 we have detected six suspicious events in the Richard B. Russell area (Figure 4). These events were detected on 11 January 1986, two on 29 January 1986 (one foreshock and the main shock), 31 March 1986, 16 April 1986, and 17 April 1986 (Figures 6a-b). The epicenters are Calhoun Falls for the events on 11 and 29 January 1986, Rocky River for the event on 31 March, and the area around the site of Station EP1 for the events on 16 and 17 April. Besides the above events, we have detected three possible events on 5 January 1986, 21 April 1986, and 22 April 1986; but since they were detected by only one station a location was not possible (Figure 7). We feel that the source of the events on 27 October 1985 and 16 and 17 April 1986 is the same. The events on 11 and 29 January 1986 probably have the same source even though the location program assigns them separate epicenters. Because of the uncertainty in picking arrival times of small events, the difference in location can be considered within the range of uncertainty of location capability (Figures 8a-h).

Prior to January 1986, only a few of these events seemed to be occurring at isolated times. However, the events detected in the last few months indicate that the seismicity may be increasing. In Figures 9-11 the seismicity of Richard B. Russell Reservoir as well as the fluctuation of the Lake's water level for the years 1983, 1984, 1985 is shown.
Table 1. Station Operation Periods

<table>
<thead>
<tr>
<th>Month</th>
<th>CHF</th>
<th>IVA</th>
<th>BEV</th>
<th>LDV</th>
<th>One Station Coverage</th>
<th>Two Station Coverage</th>
<th>Three Station Coverage</th>
<th>Four Station Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>94%</td>
<td>26%</td>
<td>97%</td>
<td>0%</td>
<td>100%</td>
<td>94%</td>
<td>23%</td>
<td>0%</td>
</tr>
<tr>
<td>February</td>
<td>46%</td>
<td>82%</td>
<td>100%</td>
<td>0%</td>
<td>100%</td>
<td>86%</td>
<td>32%</td>
<td>0%</td>
</tr>
<tr>
<td>March</td>
<td>94%</td>
<td>52%</td>
<td>100%</td>
<td>0%</td>
<td>100%</td>
<td>97%</td>
<td>48%</td>
<td>0%</td>
</tr>
<tr>
<td>April</td>
<td>67%</td>
<td>73%</td>
<td>77%</td>
<td>67%</td>
<td>77%</td>
<td>77%</td>
<td>73%</td>
<td>63%</td>
</tr>
<tr>
<td>May</td>
<td>84%</td>
<td>97%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>81%</td>
</tr>
<tr>
<td>June</td>
<td>0%</td>
<td>100%</td>
<td>100%</td>
<td>93%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>93%</td>
</tr>
<tr>
<td>July</td>
<td>55%</td>
<td>71%</td>
<td>100%</td>
<td>94%</td>
<td>100%</td>
<td>97%</td>
<td>68%</td>
<td>58%</td>
</tr>
<tr>
<td>August</td>
<td>3%</td>
<td>23%</td>
<td>39%</td>
<td>29%</td>
<td>39%</td>
<td>29%</td>
<td>23%</td>
<td>3%</td>
</tr>
<tr>
<td>September</td>
<td>20%</td>
<td>50%</td>
<td>93%</td>
<td>83%</td>
<td>97%</td>
<td>87%</td>
<td>50%</td>
<td>13%</td>
</tr>
<tr>
<td>October</td>
<td>71%</td>
<td>58%</td>
<td>97%</td>
<td>77%</td>
<td>100%</td>
<td>94%</td>
<td>74%</td>
<td>32%</td>
</tr>
<tr>
<td>November</td>
<td>0%</td>
<td>37%</td>
<td>67%</td>
<td>23%</td>
<td>67%</td>
<td>37%</td>
<td>23%</td>
<td>0%</td>
</tr>
<tr>
<td>December</td>
<td>6%</td>
<td>23%</td>
<td>81%</td>
<td>81%</td>
<td>81%</td>
<td>81%</td>
<td>29%</td>
<td>0%</td>
</tr>
</tbody>
</table>

Average Coverage

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<th></th>
<th>CHF</th>
<th>IVA</th>
<th>BEV</th>
<th>LDV</th>
<th>One Station Coverage</th>
<th>Two Station Coverage</th>
<th>Three Station Coverage</th>
<th>Four Station Coverage</th>
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<tr>
<td>Average</td>
<td>45%</td>
<td>58%</td>
<td>88%</td>
<td>54%</td>
<td>88%</td>
<td>82%</td>
<td>53%</td>
<td>21%</td>
</tr>
</tbody>
</table>

Explanation of Station Coverage

Station coverage is broken down as follows:

One Station Coverage — the percentage of time that at least one of the four stations is functioning normally.

Two Station Coverage — the percentage of time that at least two of the four stations are functioning normally.

Three Station Coverage — the percentage of time that at least three of the four stations are functioning normally.

Four Station Coverage — the percentage of time that all four stations are functioning normally.
Figure 5a. Seismograms of suspected induced event.
Figure 5b. Seismograms of suspected induced events.
Figure 6a. Seismograms of suspected induced events.
Figure 6b. Seismograms of suspected induced events.
Figure 7. Seismograms of suspected induced events.
THE EVENT OCCURED ON JAN 29, 1985
AT ORIGIN TIME 1:56:57.69 +/- .219
DANBURG
MAGNITUDE: 1.8
THE WEIGHTS ARE
WX= 1.000 WY= 1.000 WZ= 0.000 WT= 1.000
IT WAS LOCATED AT
LATITUDE 33.8751 +/- 1.079 KM. (33D,52.51M)
LONGITUDE 82.6531 +/- 1.054 KM. (82D,39.19M)
DEPTH 0.00 +/- 0.000 KM.

STATION PHASE HR MIN SEC +OR-SEC DIST AZ OBS-THE THEOR.
CHF PG 1 57 1.00 .10 17.69 20.3 .096 7020.90
BEV PG 1 57 2.00 .10 24.89 342.7 -.213 7022.21
BEV S 1 57 5.60 .10 24.89 342.7 .073 7025.53
RCT PLG 1 57 39.00 .10 247.22 311.8 .050 7058.95
RHT PLG 1 57 38.90 .10 245.66 303.3 .207 7058.69
TLT PLG 1 57 34.00 .10 218.55 316.8 -.212 7054.21

DIAGONAL ELEMENTS
1.9660 1.9205 .3995

COVARIANCE MATRIX:

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<th></th>
<th>38.653</th>
<th>10.110</th>
<th>4.600</th>
<th>0.000</th>
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<td>10.110</td>
<td>36.883</td>
<td>6.698</td>
<td>0.000</td>
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<tr>
<td>4.600</td>
<td>6.698</td>
<td>1.596</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td></td>
</tr>
</tbody>
</table>

ERROR ELLIPSE IS AS FOLLOWS:
MINOR AXIS LENGTH = 1.1771 KM.
MAJOR AXIS LENGTH = 1.5504 KM.
AZIMUTH OF MAJOR AXIS = 137.5027 DEG.
AREA OF ELLIPSE = 5.7333 SQ.KM.

MEAN RESIDUAL : .00020 STANDARD DEVIATION : .17349

Figure 8a. Computer location of the January 29, 1985, suspected reservoir induced event.
THE EVENT OCCURRED ON OCT 27, 1985
AT ORIGIN TIME 3:22:51.33 +/- .064
CALHOUN FALLS
MAGNITUDE: 0.8
THE WEIGHTS ARE
WX = 1.000  WY = 1.000  WZ = 0.000  WT = 1.000
IT WAS LOCATED AT
LATITUDE 33.9763 +/- .771 KM. (33D,58.58M)
LONGITUDE 82.5535 +/- .428 KM. (82D,33.21M)
DEPTH 0.00 +/- 0.000 KM.

<table>
<thead>
<tr>
<th>STATION</th>
<th>PHASE</th>
<th>HR</th>
<th>MIN</th>
<th>SEC +OR-SEC</th>
<th>DIST</th>
<th>AZ</th>
<th>OBS-THE</th>
<th>THEOR.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH6</td>
<td>PG</td>
<td>3</td>
<td>22</td>
<td>53.20 .10</td>
<td>9.42</td>
<td>166.1</td>
<td>.155</td>
<td>12173.04</td>
</tr>
<tr>
<td>CH6</td>
<td>S</td>
<td>3</td>
<td>22</td>
<td>54.20 .10</td>
<td>9.42</td>
<td>166.1</td>
<td>-.099</td>
<td>12174.30</td>
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<tr>
<td>IVA</td>
<td>PG</td>
<td>3</td>
<td>22</td>
<td>58.00 .10</td>
<td>37.32</td>
<td>331.6</td>
<td>-.105</td>
<td>12178.11</td>
</tr>
<tr>
<td>IVA</td>
<td>S</td>
<td>3</td>
<td>23</td>
<td>3.00 .10</td>
<td>37.32</td>
<td>331.6</td>
<td>.048</td>
<td>12182.95</td>
</tr>
<tr>
<td>BEV</td>
<td>PG</td>
<td>3</td>
<td>22</td>
<td>55.10 .10</td>
<td>20.81</td>
<td>307.0</td>
<td>-.016</td>
<td>12175.12</td>
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<tr>
<td>BEV</td>
<td>S</td>
<td>3</td>
<td>22</td>
<td>57.90 .10</td>
<td>20.81</td>
<td>307.0</td>
<td>.014</td>
<td>12177.89</td>
</tr>
</tbody>
</table>

DIAGONAL ELEMENTS
2.4965  1.3842  .2075

COVARIANCE MATRIX:

\[
\begin{bmatrix}
62.324 & -30.696 & 4.018 & 0.000 \\
-30.696 & 19.161 & -1.838 & 0.000 \\
4.018 & -1.838 & .431 & 0.000 \\
0.000 & 0.000 & 0.000 & 0.000
\end{bmatrix}
\]

ERROR ELLIPSE IS AS FOLLOWS:
MINOR AXIS LENGTH = .2262 KM.
MAJOR AXIS LENGTH = 1.1155 KM.
AZIMUTH OF MAJOR AXIS = 27.4450 DEG.
AREA OF ELLIPSE = .7929 SQ.KM.

MEAN RESIDUAL: -.00046  STANDARD DEVIATION: .09767

Figure 8b. Computer location of the October 27, 1985, suspected reservoir induced earthquake.
THE EVENT OCCURRED ON DEC 13, 1985
AT ORIGIN TIME 5: 9:41.43 +/- .237
ANTREVILLE
MAGNITUDE: 1.2
THE WEIGHTS ARE
WX= 1.000  WY= 1.000  WZ= 0.000  WT= 1.000
IT WAS LOCATED AT
LATITUDE  34.3527 +/- .859 KM.  (34D,21.16M)
LONGITUDE  82.4291 +/- 1.105 KM.  (82D,25.75M)
DEPTH  0.00 +/- 0.000 KM.

STATION PHASE  HR  MIN  SEC + OR-SEC  DIST  AZ  OBS-THE  THEOR.
LDV  PG  5  9 47.60 .10   32.60  225.9  .241 18587.36
LDV  S  5  9 51.70 .10   32.60  225.9  .001 18591.70
BEV  PG  5  9 48.50 .10  40.46  223.9  -.226 18588.73
BEV  S  5  9 53.90 .10  40.46  223.9  -.037 18593.94
CH6  PG  5  9 50.60 .10  51.72  190.3  .014 18590.59
CH6  S  5  9 57.10 .10  51.72  190.3  .001 18597.10

DIAGONAL ELEMENTS
1.8291  2.3528  .5036

COVARIANCE MATRIX:
33.455  .676  4.026  0.000
 .676 55.355 -10.132 0.000
 4.026 -10.132  2.536 0.000
 0.000  0.000  0.000 0.000

ERROR ELLIPSE IS AS FOLLOWS:
MINOR AXIS LENGTH  =  1.1090 KM.
MAJOR AXIS LENGTH  =  1.4273 KM.
AZIMUTH OF MAJOR AXIS  =  91.7655 DEG.
AREA OF ELLIPSE  =  4.9726 SQ.KM.

MEAN RESIDUAL :  -.00099  STANDARD DEVIATION :  .14856

Figure 8c. Computer location of the December 13, 1985, suspected reservoir induced earthquake.
THE EVENT OCCURRED ON JAN 11, 1986
AT ORIGIN TIME 3:10:12.22 +/- .053

MAGNITUDE: -0.2

THE WEIGHTS ARE
WX= 1.000 WY= 1.000 WZ= 0.000 WT= 1.000

IT WAS LOCATED AT
LATITUDE 34.0709 +/- .392 KM. (34D, 4.26M)
LONGITUDE 82.6135 +/- .317 KM. (82D,36.81M)
DEPTH 0.00 +/- 0.000 KM.

<table>
<thead>
<tr>
<th>STATION</th>
<th>PHASE</th>
<th>HR</th>
<th>MIN</th>
<th>SEC</th>
<th>+OR-SEC</th>
<th>DIST</th>
<th>AZ</th>
<th>OBS-THE</th>
<th>THEOR.</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDV</td>
<td>PG</td>
<td>3</td>
<td>10</td>
<td>14</td>
<td>0.20</td>
<td>10.69</td>
<td>323.0</td>
<td>.039</td>
<td>11414.16</td>
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<tr>
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<td>S</td>
<td>3</td>
<td>10</td>
<td>15</td>
<td>0.50</td>
<td>10.70</td>
<td>323.0</td>
<td>-.085</td>
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<tr>
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<td>PG</td>
<td>3</td>
<td>10</td>
<td>14</td>
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<td>11.27</td>
<td>280.4</td>
<td>.134</td>
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<tr>
<td>BEV</td>
<td>S</td>
<td>3</td>
<td>10</td>
<td>15</td>
<td>0.70</td>
<td>11.27</td>
<td>280.4</td>
<td>-.066</td>
<td>11415.77</td>
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<tr>
<td>CH6</td>
<td>PG</td>
<td>3</td>
<td>10</td>
<td>16</td>
<td>1.10</td>
<td>21.14</td>
<td>158.3</td>
<td>.040</td>
<td>11416.06</td>
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<tr>
<td>CH6</td>
<td>S</td>
<td>3</td>
<td>10</td>
<td>18</td>
<td>8.80</td>
<td>21.14</td>
<td>158.3</td>
<td>-.074</td>
<td>11418.87</td>
</tr>
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</table>

DIAGONAL ELEMENTS
1.4200  1.1505  .1904

COVARIANCE MATRIX:

\[
\begin{pmatrix}
20.163 & -12.934 & 1.987 & 0.000 \\
-12.934 & 13.236 & -1.256 & 0.000 \\
1.987 & -1.256 & .363 & 0.000 \\
0.000 & 0.000 & 0.000 & 0.000
\end{pmatrix}
\]

ERROR ELLIPSE IS AS FOLLOWS:
MINOR AXIS LENGTH = .2050 KM.
MAJOR AXIS LENGTH = .6179 KM.
AZIMUTH OF MAJOR AXIS = 37.5044 DEG.
AREA OF ELLIPSE = .3979 SQ.KM.

MEAN RESIDUAL : .00189 STANDARD DEVIATION : .08724

Figure 8d. Computer location of the January 11, 1986, suspected reservoir induced earthquake.
### Foreshock

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Origin Time</td>
<td>08:17:11.66 ± 0.170</td>
</tr>
<tr>
<td>Latitude</td>
<td>34.0626° ± 0.664 km</td>
</tr>
<tr>
<td>Longitude</td>
<td>82.6409° ± 0.870 km</td>
</tr>
<tr>
<td>Depth</td>
<td>1 km</td>
</tr>
<tr>
<td>Magnitude</td>
<td>-2</td>
</tr>
</tbody>
</table>

**BEV S-P** 1.1 sec, **Duration**: 10 sec

**CH6 S-P** 2.8 sec, **Duration**: 10 sec

**PRM**
- P 08:17:16.4
- S 08:17:20.0

### Main Shock

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Origin Time</td>
<td>08:17:23.16 ± 0.174</td>
</tr>
<tr>
<td>Latitude</td>
<td>34.0203° ± 0.722 km</td>
</tr>
<tr>
<td>Longitude</td>
<td>82.7006° ± 0.644 km</td>
</tr>
<tr>
<td>Depth</td>
<td>1 km</td>
</tr>
<tr>
<td>Magnitude</td>
<td>1.3</td>
</tr>
</tbody>
</table>

**BEV S-P** 1.0 sec, **Duration**: 45 sec

**CH6 S-P** 2.7 sec, **Duration**: 46 sec

**JSC**
- P 08:17:46.0, **Duration**: 50 sec

**PRM**
- P 08:17:29.0, **Duration**: 50 sec

Figure 8e. Computer locations of the January 29, 1986, suspected reservoir induced earthquakes.
THE EVENT OCCURRED ON MAR 31, 1986
AT ORIGIN TIME 1:54:45.20 +/- 0.045
ROCKY RIVER
MAGNITUDE: 0.4

THE WEIGHTS ARE
WX = 1.000 WY = 1.000 WZ = 0.000 WT = 1.000

IT WAS LOCATED AT
LATITUDE 34.0275 +/- 0.506 KM. (34D, 1.65M)
LONGITUDE 82.6007 +/- 0.359 KM. (82D, 36.04M)
DEPTH 0.00 +/- 0.000 KM.

<table>
<thead>
<tr>
<th>STATION PHASE</th>
<th>HR MIN SEC +OR-SEC</th>
<th>DIST</th>
<th>AZ</th>
<th>OBS-THE THEOR.</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEV PG</td>
<td>1 54 47.90 .10</td>
<td>14.04 299.2</td>
<td>.144</td>
<td>6887.76</td>
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<tr>
<td>BEV S</td>
<td>1 54 49.55 .10</td>
<td>14.03 299.2</td>
<td>-.073</td>
<td>6889.62</td>
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<tr>
<td>LDV PG</td>
<td>1 54 48.00 .10</td>
<td>15.38 330.3</td>
<td>-.003</td>
<td>6888.00</td>
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<tr>
<td>LDV S</td>
<td>1 54 50.00 .10</td>
<td>15.38 330.3</td>
<td>-.050</td>
<td>6890.05</td>
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<tr>
<td>CH6 PG</td>
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<td>16.23 155.9</td>
<td>.043</td>
<td>6888.16</td>
</tr>
<tr>
<td>CH6 S</td>
<td>1 54 50.25 .10</td>
<td>16.23 155.9</td>
<td>-.067</td>
<td>6890.32</td>
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</table>

DIAGONAL ELEMENTS
1.9178 1.3591 .1699

COVARIANCE MATRIX:

\[
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36.781 & -22.846 & 2.067 & 0.000 \\
-22.846 & 18.472 & -1.126 & 0.000 \\
2.067 & -1.126 & 0.289 & 0.000 \\
0.000 & 0.000 & 0.000 & 0.000 \\
\end{bmatrix}
\]

ERROR ELLIPSE IS AS FOLLOWS:
MINOR AXIS LENGTH = .1871 KM.
MAJOR AXIS LENGTH = .7790 KM.
AZIMUTH OF MAJOR AXIS = 34.0821 DEG.
AREA OF ELLIPSE = .4580 SQ.KM.

MEAN RESIDUAL : -.00097 STANDARD DEVIATION : .08348

Figure 8f. Computer location of the March 31, 1986, suspected reservoir induced earthquake.
THE EVENT OCCURRED ON APR 16, 1986
AT ORIGIN TIME 8:51:45.43 +/- .056
EP1
MAGNITUDE: 0.2
THE WEIGHTS ARE
WX= 1.000 WY= 1.000 WZ= 0.000 WT= 1.000
IT WAS LOCATED AT
LATITUDE 33.9592 +/- .999 KM. (33D,57.55M)
LONGITUDE 82.5610 +/- .589 KM. (82D,33.66M)
DEPTH 0.00 +/- 0.000 KM.

STATION PHASE HR MIN SEC +OR-SEC DIST ' AZ OBS-THE THEOR.
CH6 PG 8 51 46.80 .10 7.83 157.9 -.054 31906.85
CH6 S 8 51 47.90 .10 7.83 157.9 .003 31907.90
LDV PG 8 51 49.90 .10 23.78 331.7 .147 31909.75
LDV S 8 51 52.80 .10 23.78 331.7 -.118 31912.92
BEV S 8 51 52.20 .10 21.46 312.2 .010 31912.19

DIAGONAL ELEMENTS
3.2206 1.9008 .1803

COVARIANCE MATRIX:

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<td>36.130</td>
<td>-1.807</td>
<td>0.000</td>
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<tr>
<td>-57.770</td>
<td>36.130</td>
<td>-1.807</td>
<td>.325</td>
<td>0.000</td>
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<tr>
<td>3.515</td>
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<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

ERROR ELLIPSE IS AS FOLLOWS:
MINOR AXIS LENGTH = .2401 KM.
MAJOR AXIS LENGTH = 1.6229 KM.
AZIMUTH OF MAJOR AXIS = 29.8364 DEG.
AREA OF ELLIPSE = 1.2242 SQ.KM.

MEAN RESIDUAL : -.00249 STANDARD DEVIATION : .09805

Figure 8g. Computer location of the April 16, 1986, suspected reservoir induced earthquake.
THE EVENT OCCURED ON APR 17, 1986
AT ORIGIN TIME 9:53:57.94 +/- .127
EP1
MAGNITUDE: 0.2
THE WEIGHTS ARE
WX = 1.000 WY = 1.000 WZ = 0.000 WT = 1.000
IT WAS LOCATED AT
LATITUDE 33.9271 +/- .570 KM. (33D, 55.63M)
LONGITUDE 82.4459 +/- .234 KM. (82D, 26.75M)
DEPTH 0.00 +/- 0.000 KM.

STATION PHASE HR MIN SEC +OR-SEC DIST AZ OBS-THE THEOR.
CH6 PG 9 53 59.40 .10 8.53 244.3 -.096 35639.50
CH6 S 9 54 .70 .10 8.54 244.3 .068 35640.63
LDV PG 9 54 4.00 .10 32.90 318.2 .074 35643.93
LDV S 9 54 8.30 .10 32.90 318.2 -.005 35648.31
BEV S 9 54 8.00 .10 32.12 304.1 -.057 35648.06

DIAGONAL ELEMENTS
2.4042 .9869 .5365

COVARIANCE MATRIX:

<table>
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<td>12.346</td>
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<td>0.000</td>
<td>0.000</td>
<td></td>
</tr>
</tbody>
</table>

ERROR ELLIPSE IS AS FOLLOWS:
MINOR AXIS LENGTH = .3232 KM.
MAJOR AXIS LENGTH = .8103 KM.
AZIMUTH OF MAJOR AXIS = 174.3810 DEG.
AREA OF ELLIPSE = .8228 SQ.KM.

MEAN RESIDUAL : -.00314 STANDARD DEVIATION : .07498

Figure 8h. Computer location of the April 17, 1986, suspected reservoir induced earthquake.
THE SEISMICITY OF
RICHARD B. RUSSELL
RESERVOIR
1983

Figure 9. The seismicity of the Richard B. Russell Reservoir and the fluctuation of Richard B. Russell Lake's water level for 1983.
Figure 10. The seismicity of the Richard B. Russell Reservoir and the fluctuation of Richard B. Russell Lake's water level for 1984.
Figure 11. The seismicity of the Richard B. Russell Reservoir and the fluctuation of Richard B. Russell Lake's water level for 1985.
We were unable to identify an alternate explanation for these events, but we cannot at this time rule out road or other construction activity as a source. The earthquake locations are not sufficiently precise to associate them with known faults or structures in the area. However, upon inspection of a preliminary geological reconnaissance map of the RBR area, a granitic gneiss/mica schist is mapped in the same area as the epicenters (Figures 12 and 13). Granitic gneiss/mica schists of a similar type are believed to be associated with induced earthquakes near other reservoirs in Georgia and South Carolina. These reservoirs include the Monticello and Jocassee Reservoirs, both in the South Carolina Piedmont geologic province. The possibility exists that this particular rock unit might be associated with the seismic events in the Richard B. Russell Reservoir area.
Figure 12. Detailed geology of the Richard B. Russell Reservoir Area. Earthquake epicenters of the events induced in 1984 are also included.

--- Explanation ---

Gr/Ms: Granitic gneiss / Mica Schist
Epv: Volcanic tuffs and lavas
Gb: Gabbro
Qs: Quartzite
Bga: Gabbro mixed with amphibolite
---: Fault
+ = Epicenter
--- Reservoir Boundary ---

KILOMETERS | 0 1 2 3 4 5 6
Figure 13. Detailed geology of the Richard B. Russell Reservoir Area. Earthquake epicenters of the events induced in 1986 are also included.
20 April 1985
Location: Athens, TN
Origin Time: 04:21:02:40

Station: PLG: 04:21:40.0
LDV     SLG: 04:22:06.0

Athens,TN

Station: PLG: 04:21:40.4
BEV     SLG: 04:22:07.0
18 October 1985
Location: Lake Jocassee, S.C.
Origin Time: 01:45:29.9
Station: PLG: 01:45:47.60
LDV
20 December 1985

Location: Tennga, Georgia
Origin Time: 15:15:06.6

Station: PLG: 15:15:40.0
BEV SLG: 15:16:04.5
22 December 1985
Location: Gregory Bald Mountain, N.C.
Origin Time: 00:56:05.1

Station : PLG: 00:56:37.2
BEV SLG: 00:57:00.0

Gregory Bald Mountain, N.C.

Station : PLG: 00:56:36.9
LDV SLG: 00:56:59.0
7 January 1986
Location: Decatur, TN
Origin Time: 01:26:43.95

Station: PLG: 01:27:23.0
BEV SLG: 01:27:50.0

Decatur, TN
Station: PLG: 01:27:24.0
LDV SLG: 01:27:52.2
13 February 1986
Location: Lake Keowee, South Carolina
Origin Time: 11:35:46.92
Station: P: 11:35:59.10
BEV S: 11:36:07.90

Lake Keowee, South Carolina
Station: P: 11:35:58.2
LDV S: 11:36:06.9
13 February 1986
Location: Lake Keowee, South Carolina

Station: P: 13:53:35.0
BEV S: 13:53:44.0

Lake Keowee, South Carolina

Station: P: 13:53:36.2
LDV S: 13:53:45.0
BIBLIOGRAPHY

