ATTACHMENT 1

THE LAKE KEOWEE EARTHQUAKES OF JUNE-JULY, 1986

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INTRODUCTION

A series of earthquakes occurred near Lake Keowee in northwestern South Carolina in June-July 1986. At least four shocks of this series were felt in the surrounding area. In order to obtain accurate locations portable seismographs were deployed in the epicentral region. The results of this study are the subject of this report.

THE JUNE-JULY SWARMS

At 12:12 EST (1612 UTC) on June 11, 1986, an earthquake of approximate local magnitude 2.8 occurred near Lake Keowee and was felt in the surrounding area. Portable seismographs were deployed (Figure 1) in the epicentral region within twenty four hours of the main shock. An additional twenty seven earthquakes were recorded over the following three day period, of which five were accurately located. These events lay outside the epicentral areas of the microearthquake swarm of January-February 1978 (Talwani *et al.*, 1979) and that of the microearthquake activity observed in February 1986 (Rawlins and Acree, 1986). (Note, the locations obtained for the February 1986 earthquakes reported in Rawlins and Acree (1986) have been revised. Revised locations of the B quality events lie approximately 0.5 km to the southwest of the January-February 1978 activity. A summary of the revised locations is presented in Appendix A.) Instead, the trend of accurately located June aftershocks is perpendicular to the major axis of the ellipse defined by the 1978 swarm (Figure 2). Earthquakes at Lake Keowee were identified on seismograms from the

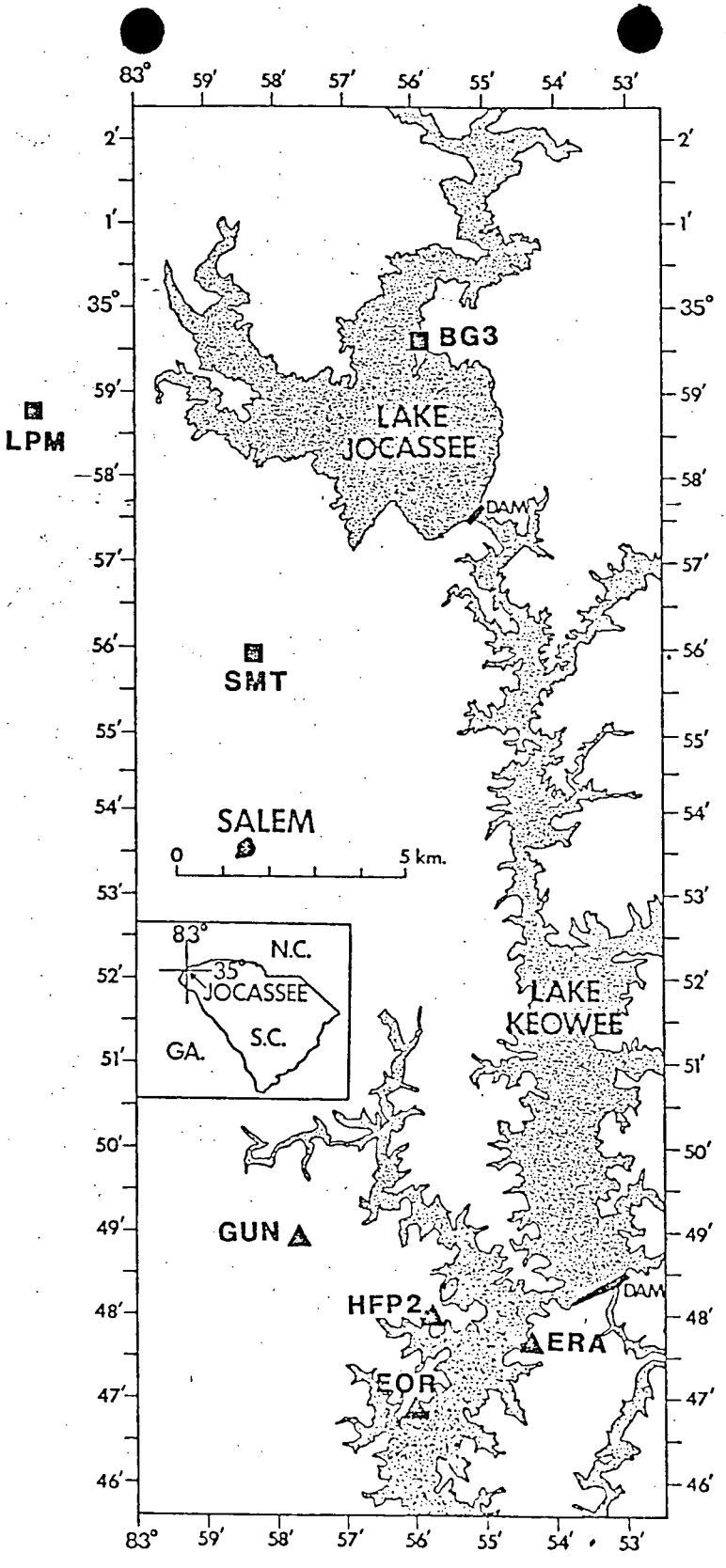

Figure 1. Location of portable seismic network deployed June 11-14, 1986, relative to stations of the Jocassee network.

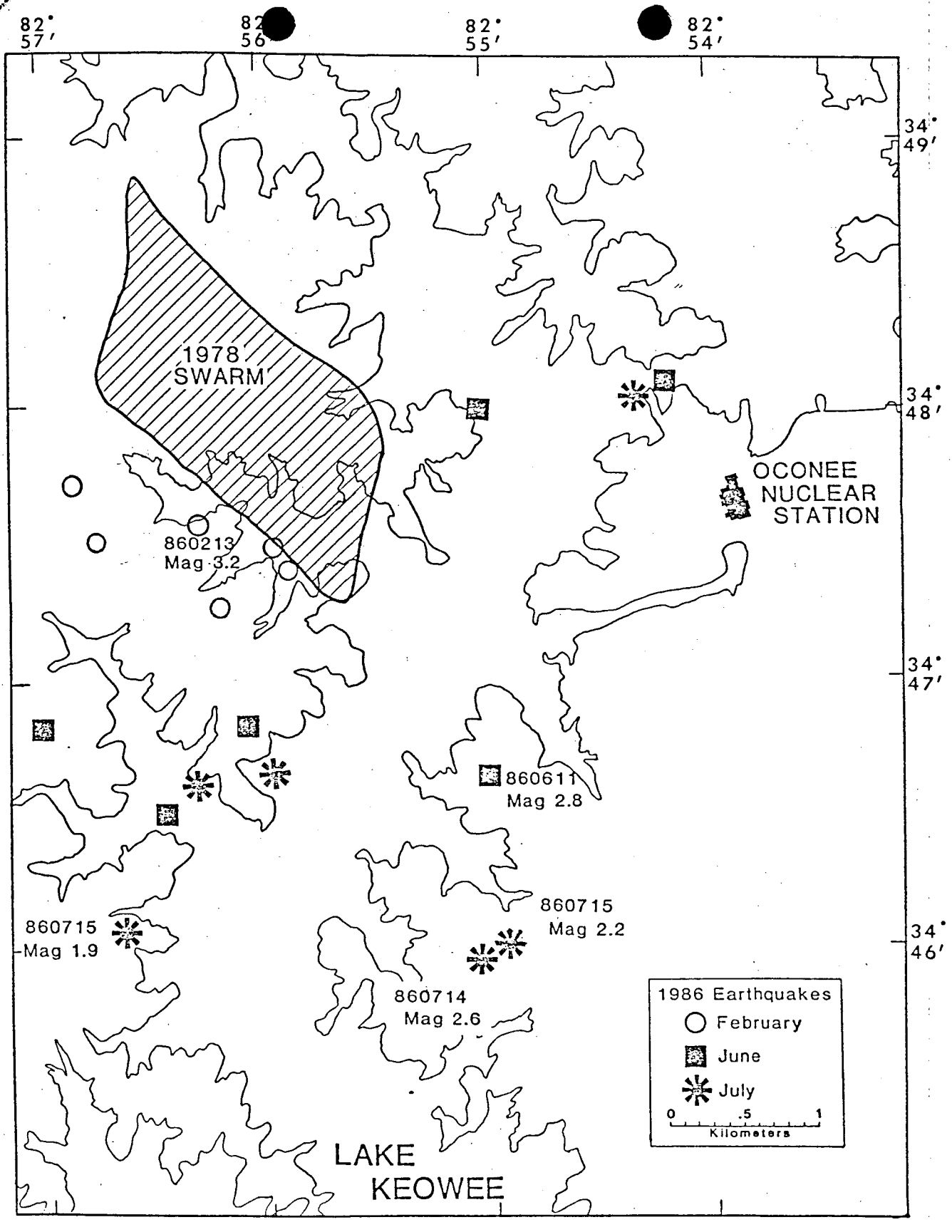

Figure 2. Locations of Lake Keowee seismicity (June-July 1986) relative to those of the January-February 1978 swarm and the quality B locations of February 1986.

Lake Jocassee network by characteristic S-P times. These shocks were not always locatable but indicated activity at Lake Keowee continued and increased during the second week in July (Figure 3). Over thirty Keowee events were identified in the period June 14-July 18, at least three of which were felt. Six of these events were located (Figure 2) using data from the Jocassee and South Carolina seismic networks.

Main Shock - June 11, 1986

Using stations of the Duke Power, Tennessee Earthquake Information Center, Georgia Institute of Technology, and U.S. Geological Survey - University of South Carolina networks and a velocity model for the Jocassee region (Table I) the main shock of June 11 was located with the computer algorithm HYPO71 (Lee and Lahr, 1972) at 34° 46.63' N latitude and 82° 54.97' W longitude (Table II). The calculated origin time was 16:12:01 UTC. The epicenter was located approximately 2.4 km southwest of the Oconee Nuclear Station as shown in Figure 2. The local magnitude of 2.8 was obtained from the durations at stations PRM and JSC of South Carolina seismic network.

June 1986 Aftershocks

Portable seismographs were deployed in the previously defined epicentral area (Figure 1) late on June 11 and monitored until June 14, when it was determined that activity had diminished. Twenty seven aftershocks with durations of three seconds or greater were recorded during this period. The largest after-

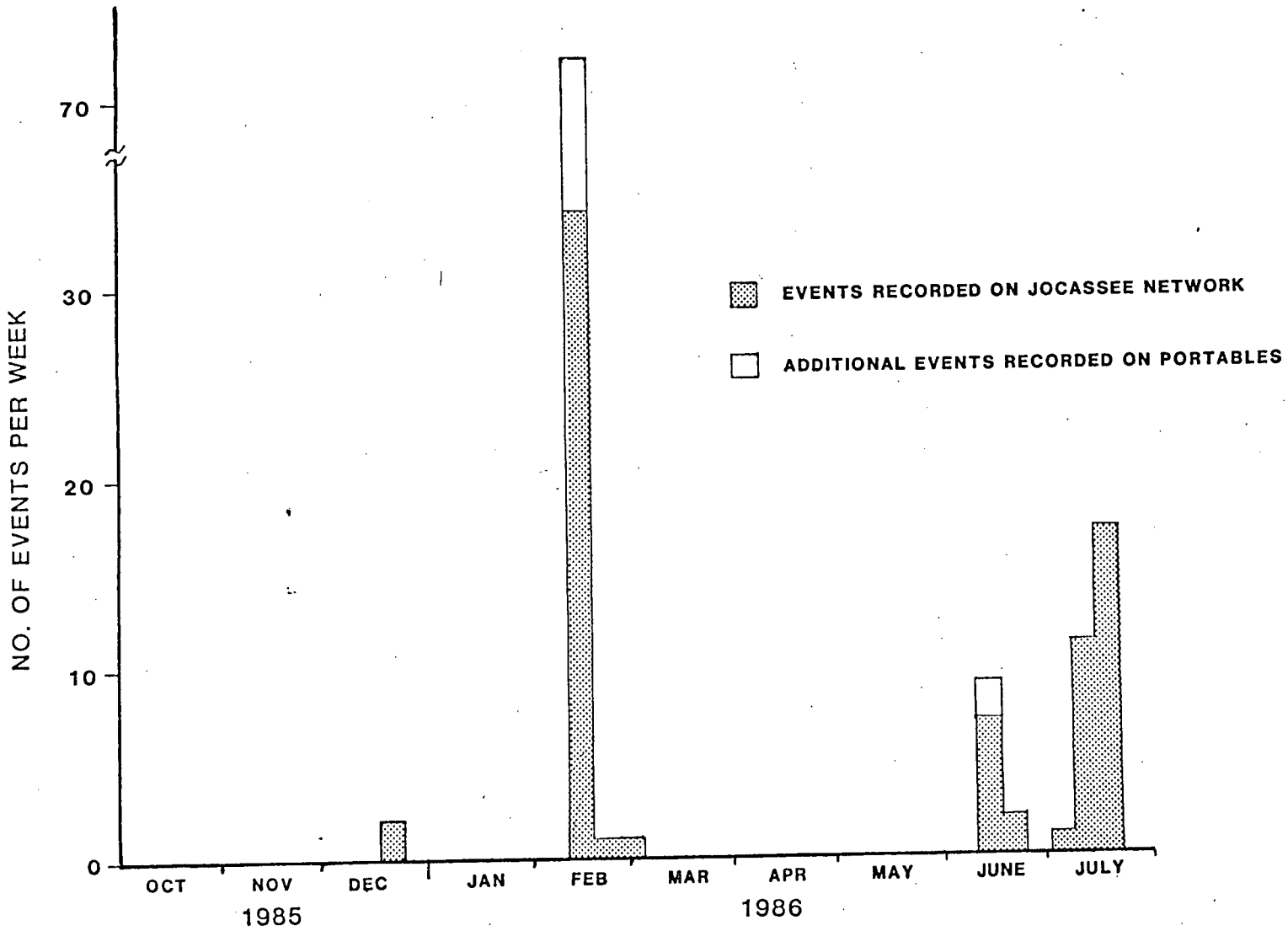

Figure 3. Number of Lake Keowee events per week (October 1, 1985 - July 18, 1986) identified from records of the Lake Jocassee seismic network and from portable seismographs deployed in the epicentral area.

TABLE I

LAKE JOCASSEE

VELOCITY MODEL

Velocity km/sec	Depth to top km
4.50	0.00
5.75	0.28
6.20	1.22
8.15	33.75

TABLE II

LAKE KEOWEE EARTHQUAKES LOCATED
JUNE - JULY 1986

HYPO71 FORMAT

Column 1	Date.
Column 2	Origin time (UCT) h.m.sec.
Column 3	Latitude (N) degrees, min.
Column 4	Longitude (W) degrees, min.
Column 5	Depth (km).
Column 6	Local duration magnitude.
Column 7	No. of station readings used to locate event. P and S arrivals from same stations are regarded as 2 readings.
Column 8	Largest azimuthal separation in degrees between stations.
Column 9	Epicentral distance in km to nearest station.
Column 10	Root mean square error of time residuals in sec. RMS = R_i^2/NO, where R_i is the time residual for the ith station.
Column 11	Standard error of the epicenter in km*.
Column 12	Standard error of the focal depth in km*.

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*Statistical interpretation of standard errors involves assumptions which may not be met in earthquake locations. Therefore standard errors may not represent actual error limits.

If ERH or ERZ is blank, this means that it cannot be computed, because of insufficient data.

LAKE KEOWEE EARTHQUAKES OF JUNE - JULY, 1986.

JUNE 1986

DATE	ORIGIN H	M	S	LAT N D	MIN	LONG W D	MIN	DEPTH KM	MAG	NO	GAP	DMIN KM	RMS S	ERH KM	ERZ KM	QM
860611	1612		0.53	34-46.63		82-54.97		2.98	2.78	31	89	24.0	0.07	0.2	3.0	C1
860612	1853		40.85	34-48.09		82-54.19		0.18	-0.20	5	302	2.6	0.02	0.6	0.7	C1
860612	1853		52.89	34-47.99		82-55.05		0.58	-0.32	5	279	1.3	0.00	0.2	0.4	C1
860613	154		43.73	34-46.83		82-57.02		2.37	0.00	10	246	1.5	0.05	0.6	0.5	C1
860613	341		48.95	34-46.83		82-56.11		2.24	-0.15	10	187	0.2	0.05	0.5	0.3	C1
860614	332		34.04	34-46.50		82-56.46		1.03	-0.49	8	277	0.8	0.07	0.6	0.6	C1

JULY 1986

DATE	ORIGIN H	M	S	LAT N D	MIN	LONG W D	MIN	DEPTH KM	MAG	NO	GAP	DMIN KM	RMS S	ERH KM	ERZ KM	QM
860714	2231		21.19	34-45.95		82-55.11		1.85	2.56	11	192	18.9	0.08	0.9	20.5	D1
860715	224		50.77	34-48.04		82-54.34		5.36	1.77	7	220	15.6	0.04	0.8	2.1	C1
860715	1244		3.82	34-46.07		82-56.64		1.24	1.81	5	233	18.3	0.02	0.6	36.9	D1
860715	1728		49.83	34-46.01		82-54.96		1.25	2.20	9	191	18.9	0.08	0.9	100.7	D1
860715	2035		13.36	34-46.60		82-56.32		3.00	1.71	5	231	17.4	0.01	0.5	2.7	C1
860718	143		51.58	34-46.66		82-55.96		3.16	1.44	7	230	17.3	0.05	1.0	6.5	D1

shock recorded was of approximate local magnitude 2.0 (June 11, 1621 UTC) but was not locatable. Magnitudes were determined from the durations at stations of the portable network and the Jocassee network when possible. Otherwise, the durations at stations of the Jocassee network were employed. The remaining events were small (M_L < 0.5). A total of 5 aftershocks were located accurately (Table II). These earthquakes appear to trend in a northeasterly direction (Figure 2) toward the Oconee Nuclear Station, the northernmost event located within 1 km of the plant. These events appear to be shallow with depths less than approximately 2.5 ± ~ 1 km.

July 1986 Earthquakes

A review of seismograms (June 14-July 18) from the stations of the Jocassee network indicate activity at Lake Keowee continued during June and increased in July (Figure 3) as did the energy release associated with these shocks (Figure 4). An estimate of the weekly energy release was determined using a simplified magnitude (M_L) energy (E) relation developed by Gutenberg and Richter (1956).

$$\log_{10} E = 11.8 + 1.5 M_L$$

Thirty four additional Lake Keowee earthquakes were identified from these records by their characteristic S-P times at the Lake Jocassee stations. At least three of these events were felt at the Oconee plant and in the surrounding area. These occurred on

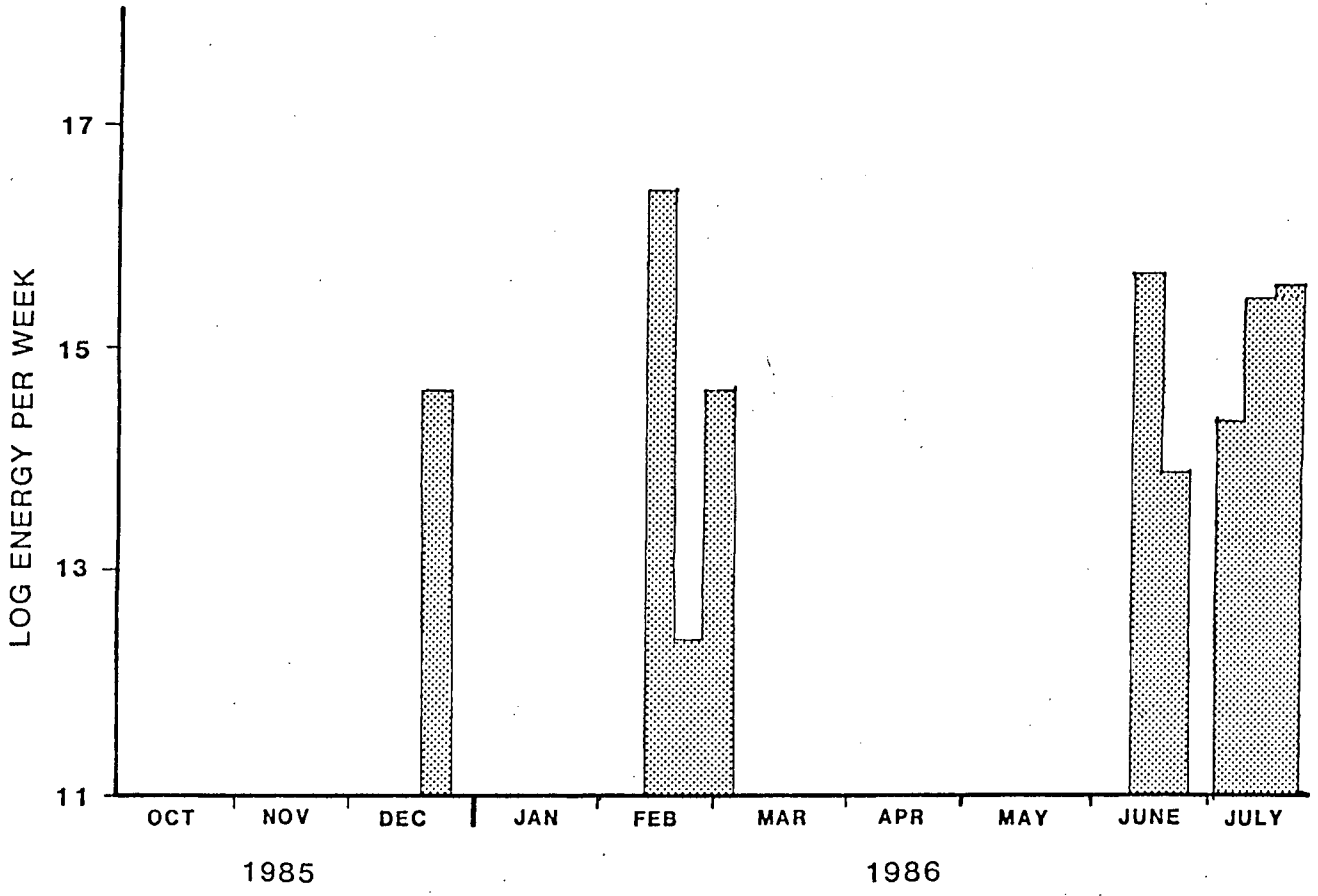

Figure 4. Plot of the log of the energy released per week during Lake Keowee earthquakes from October 1, 1985 thru July 18, 1986.

July 14 at 2231 UTC (M_L ~ 2.6) and on July 15 at 1244 UTC (M_L ~ 1.8) and 1728 UTC (M_L ~ 2.2). Twenty eight of these earthquakes were of magnitudes between 1.0 and 2.0 and two shocks were of magnitudes greater than 2.0. Magnitudes of these events were determined from the durations of stations of the Jocassee network. Six of these events were located using data from the Jocassee and South Carolina seismic networks (Figure 2). These locations are not as accurate as those of the June swarm as there were no seismographs in the epicentral area. Depths computed for these events ranged from 1.2 to 5.4 km with large vertical errors (Table II) and are not reliable. Though the accuracy of the locations is comparatively poor, there is no question of their spatial association with Lake Keowee.

SUMMARY

After a relative quiescence in preceding years, seismic activity at Lake Keowee appears to be increasing with over 120 events recorded since February 1, 1986. The largest of these earthquakes to date has been the magnitude 3.2 event of February 13 with over 25 shocks greater than magnitude 1.5 recorded through July 18. At least seven events have been felt in the last six months.

The depths of some of these events in 1986 are possibly deeper than the approximate depth extent of 2.5 km determined for the January-February 1978 swarm (Talwani *et al.*, 1979). Depths determined for that swarm were based on locations obtained using a large number of portable seismographs. The shallow depths

obtained for the June 1986 aftershocks were also based on locations utilizing portable stations. Depths calculated for the February 1986 aftershocks with a location quality of B ranged to ~ 5.4 (± ~ 1) km. These locations utilized data from one to two portable stations and are considered plausible. None of the located events in July 1986 utilized stations in the epicentral area. Hence, the depth estimates are not considered reliable. The apparently deeper seismicity in February 1986 raises the possibility of potentially larger earthquakes than have been observed to date. Only with increased station coverage in the epicentral area can the question of depths be resolved.

The seismicity of June-July 1986 was not contained within the epicentral cluster of the January-February 1978 and adjoining February 1986 activity. Accurately located aftershocks appear to trend northeast, perpendicular to the major axis of the previously defined ellipse and toward the Oconee Nuclear Station.

Continuous seismic monitoring of Lake Keowee activity appears to be warranted. Accurate locations of microseismicity cannot be obtained using the Lake Jocassee network alone. Without better station coverage in the epicentral area, it will be difficult to determine the true extent of the seismicity and depth range. Accurate determination of these parameters has a strong bearing on the estimation of the earthquake potential in the Lake Keowee area.

REFERENCES

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Talwani, P., Stevenson, D., Amick, D., and Chiang, J. An earthquake swarm at Lake Keowee, South Carolina, *Bull. Seis. Soc. Am.*, **68**, 825-841, 1979.

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APPENDIX A

LAKE KEOWEE EARTHQUAKES LOCATED FEBRUARY 1986

HYPO71 FORMAT

Column 1	Date.
Column 2	Origin time (UCT) h.m.sec.
Column 3	Latitude (N) degrees, min.
Column 4	Longitude (W) degrees, min.
Column 5	Depth (km).
Column 6	Local duration magnitude.
Column 7	No. of station readings used to locate event. P and S arrivals from same stations are regarded as 2 readings.
Column 8	Largest azimuthal separation in degrees between stations.
Column 9	Epicentral distance in km to nearest station.
Column 10	Root mean square error of time residuals in sec. RMS = R_i^2/NO, where R_i is the time residual for the ith station.
Column 11	Standard error of the epicenter in km*.
Column 12	Standard error of the focal depth in km*.

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*Statistical interpretation of standard errors involves assumptions which may not be met in earthquake locations. Therefore standard errors may not represent actual error limits.

If ERH or ERZ is blank, this means that it cannot be computed, because of insufficient data.

TABLE A.I

LOCATIONS OF FEBRUARY 1986 EVENTS AS REPORTED IN RAWLINS AND ACREE (1986).

DATE	ORIGIN H	M	S	LAT N D	MIN	LONG W D	MIN	DEPTH KM	MAG	NO	GAP	DMIN KM	RMS S	ERH KM	ERZ KM	QM
860213	11	35	45.93	34-	47.77	82-	55.62	1.92	3.22	15	148	15.5	0.10	0.6	13.6	C1
860214	6	42	17.69	34-	49.52	82-	55.13	1.38	0.68	5	220	7.6	0.58	1.4	45.0	D1
860214	10	26	17.52	34-	47.94	82-	56.26	2.82	1.34	6	220	4.3	0.04	0.7	1.4	C1
860214	18	47	39.40	34-	47.46	82-	54.09	0.89	0.57	6	221	4.0	0.07	6.3	10.2	D1
860215	1	34	33.74	34-	47.51	82-	55.54	2.98	0.37	7	163	4.2	0.04	0.4	1.2	B1
860216	4	26	4.33	34-	47.35	82-	55.95	4.80	1.95	10	152	3.9	0.07	0.5	0.8	B1
860216	4	30	18.11	34-	48.94	82-	56.13	2.93	1.21	6	185	5.9	0.06	1.0	3.4	C1
860216	11	9	48.96	34-	45.45	82-	56.04	4.74	0.01	6	199	2.1	0.06	1.0	0.8	C1
860216	15	8	8.34	34-	48.15	82-	55.07	1.00	-0.86	5	199	5.2	0.04	5.1	8.9	D1
860216	15	8	26.16	34-	47.62	82-	55.61	2.75	1.37	8	162	4.4	0.05	0.4	1.3	B1
860217	9	2	10.25	34-	49.64	82-	56.21	1.31	-1.22	5	162	7.0	0.09	1.5	47.3	D1
860217	12	21	40.06	34-	47.53	82-	56.57	5.76	0.01	6	141	3.4	0.05	0.6	1.0	B1
860217	16	7	46.55	34-	47.83	82-	56.56	2.90	1.75	7	157	3.8	0.04	0.4	1.1	B1
860217	22	15	41.21	34-	47.33	83-	3.70	1.05	0.29	5	265	8.8	0.08	2.8	6.1	D1

TABLE A.II

REVISED LIST OF FEBRUARY 1986 EVENTS.

DATE	ORIGIN H	M	S	LAT N D	MIN	LONG W D	MIN	DEPTH KM	MAG	NO	GAP	DMIN KM	RMS S	ERH KM	ERZ KM	QM
860213	11	35	45.92	34-	47.56	82-	56.29	1.21	3.22	18	110	15.6	0.07	0.3	0.7	B1
860214	6	42	18.14	34-	48.33	82-	57.11	2.08	0.68	6	206	4.6	0.05	0.9	2.9	C1
860214	10	26	17.45	34-	47.75	82-	56.23	2.84	1.34	6	231	4.7	0.04	0.7	1.5	C1
860214	18	47	39.46	34-	47.30	82-	54.65	1.76	0.57	6	206	3.6	0.06	0.8	4.0	C1
860215	1	34	33.73	34-	47.40	82-	55.90	2.97	0.37	7	153	4.2	0.05	0.4	1.3	B1
860216	4	26	4.30	34-	47.26	82-	56.20	5.02	1.95	10	145	4.2	0.06	0.4	0.7	B1
860216	4	30	18.06	34-	48.81	82-	55.94	1.74	1.21	6	188	6.3	0.08	0.6	6.4	D1
860216	11	9	48.96	34-	45.45	82-	56.39	4.48	0.01	6	198	2.7	0.04	0.6	0.5	C1
860216	15	8	8.38	34-	48.01	82-	55.55	1.31	-0.86	5	189	5.1	0.03	0.5	22.2	D1
860216	15	8	26.13	34-	47.49	82-	55.94	2.97	1.37	8	153	4.4	0.05	0.4	1.2	B1
860217	9	2	10.23	34-	49.60	82-	56.44	2.00	-1.22	5	158	7.1	0.07	0.5	4.9	C1
860217	12	21	40.08	34-	47.52	82-	56.74	5.43	0.01	6	138	3.8	0.04	0.5	0.9	B1
860217	16	7	46.54	34-	47.72	82-	56.85	2.90	1.75	7	151	3.9	0.04	0.4	1.2	B1
860217	22	15	40.98	34-	47.00	83-	4.78	2.70	0.29	5	274	9.5	0.09	1.8	9.6	D1