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Renewed Seismicity near Monticello Reservoir, South Carolina, 1996–1999

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Abstract A surprising increase in seismicity started in and around Monticello Reservoir, South Carolina in December 1996, and by the end of 1999, over 700 earthquakes with $-0.4 \leq M_L \leq 2.5$ had been located. This seismicity occurred in a new hypocentral region and filled the gaps in earlier seismicity at depths shallower than 2 km. The seismicity occurred in four episodes each with at least one earthquake of magnitude $M_L \sim 2.0$. The new seismicity started at depths of 0.8–2 km within a previously a seismic granofel body and in its surrounding volume (episodes I and II). Episode III began more than a year later and also occurred in granofels. It was located to the east of the first two episodes and at shallower depths (from the surface to ~1.4 km deep). The seismicity then migrated less than 1 km to the north and south and occurred in granodiorites (episode IV). We speculate that the rocks in the new hypocentral regions were isolated from the regions of earlier seismicity by fractures filled with zeolites. Twenty years of reaction with water led to the reopening and weakening of the zeolite-filled fractures, allowing fluids to enter the previously aseismic regions and triggering these episodes of intense seismicity. We suggest that pore pressure migration was associated with these episodes of seismicity. Each of the four episodes was associated with two stages with different temporal and spatial patterns. In the first stage, there was a rapid increase in seismicity in a small volume. We interpret this to be associated with a rapid build-up of pore pressure. In the second stage the seismicity spread, and its activity rate decayed. We interpret this stage to be associated with the equilibration of pore pressure.

Introduction

Monticello Reservoir, South Carolina, was the location of intense reservoir-induced seismicity (RIS) after its impoundment from 3 December 1977 to 8 February 1978. During impoundment the lake level rose by about 32 m. Since then, the maximum lake level change has been less than 1.5 m. Seismicity started three weeks after the impoundment and peaked in 1978 (with over 4000 events with $M_L \geq -0.4$), then began to decay, returning to the background level in early 1990s (Fig. 1). The preimpoundment (background) seismicity level of one event/10 days was determined by examining the seismicity recorded at JSC (Fig. 2) over a four-year period from 1 November 1973 to 30 November 1977 (Talwani and Acree, 1987). Seismicity in Monticello Reservoir is largely attributable to changes in pore pressure due to diffusion rather than due to elastic effects associated with loading (Talwani and Acree, 1984; Talwani, 1997; Chen and Talwani, 2000). A surprising increase in seismicity started in December 1996 (Talwani *et al.,* 1997, 1998, 1999, 2000), and by the end of 1999, over 700 earthquakes with $-0.4 \leq M_L \leq 2.5$ had been located. This renewed seismicity occurred in four discrete spurts.

The cause of this activity about 20 years after the reservoir impoundment was enigmatic, as it occurred at a time when there were no anomalous water level changes in the reservoir. In this article, we report on the locations of these events and suggest a possible explanation for these new bursts of seismicity.

Background

Located in central South Carolina, Monticello Reservoir is the source of cooling and makeup water for the Virgil C. Summer Nuclear Station (Fig. 2). Filling of the reservoir started on 3 December 1977 and was completed on 8 February 1978 (Talwani and Acree, 1987). The reservoir has a surface area of 27 km^2 and a storage volume of 0.49 km^3. Earthquake activity started in and around the reservoir area on 25 December 1977.

A five-station seismic network was installed in early September 1977, three months before the start of reservoir impoundment, and six more seismic stations were added in May 1978. The burst of the new seismicity that started in December 1996 was located using six stations that surrounded the reservoir (Fig. 2). Since most of the new seismicity was enclosed by these stations, the location quality was comparable with that of earlier earthquake activity and

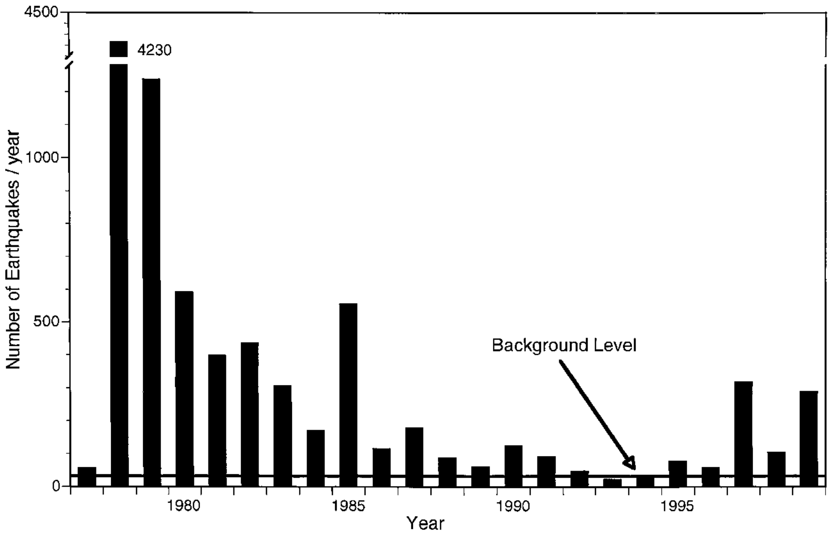

Figure 1. Annual number of earthquakes recorded at Monticello Reservoir from 1977 to 1999. The horizontal line shows the seismicity level before impoundment.

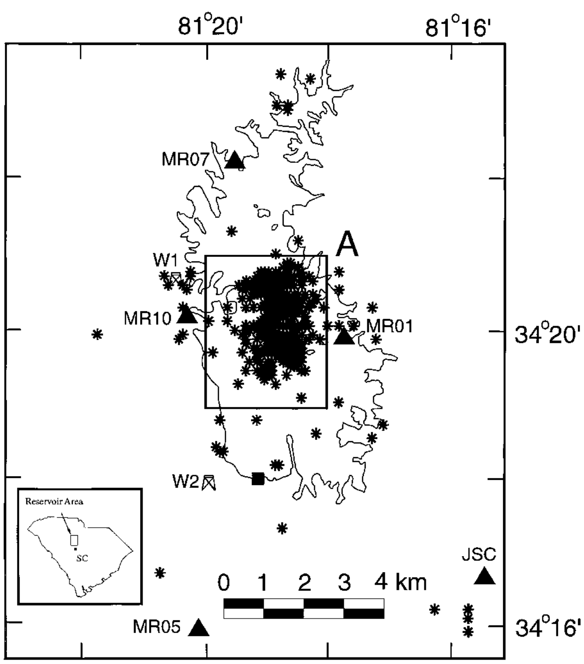

Figure 2. Shows locations of earthquakes (asterisks) at Monticello Reservoir from 15 December 1996 to 31 December 1999. Four of the 27 events that occurred ~10 km SE to the reservoir are shown, and the other 23 are outside the area covered by the figure. Inset shows the location of the reservoir area in South Carolina. Also shown are the locations of two deep wells (W1 and W2) and Virgil C. Summer Nuclear Station (solid square). The seismic stations used to located the events are shown by triangles. MR02 is located about 9 km SSE of station JSC and is shown by a small square in the inset.

thus spatial distributions could be used to search for causative mechanisms.

The seismicity at Monticello Reservoir was located using the computer program HYPO71 (Lee and Lahr, 1972) and a five-layer velocity model developed for the RIS at Monticello Reservoir (Talwani and Acree, 1987). Joint Hypocenter Determination (JHD) method developed by Pujol (1988) was also used to relocate the new seismicity. The station corrections applied in JHD partially compensate for the lateral velocity variation, thus improving the accuracy of relative hypocentral location (Pujol, 1992; Ratchkovsky *et al.,* 1997). The epicenters and depths of the relocated new seismicity using JHD were within 50 m of those obtained using conventional single-event location method by HYPO71, attesting to the accuracy of the location by HYPO71. To get a uniform data set for comparison with the earlier seismicity, we used the locations of the new seismicity obtained by using the output of HYPO71.

Recent Seismicity (December, 1996 to December, 1999)

The new intense seismicity started on 15 December 1996, and by the end of 1999, 719 earthquakes occurred in Monticello Reservoir area. Based on the temporal distribution, the sudden increases in seismicity were divided into four episodes (Fig. 3, and Table 1). The first two episodes in 1996–1997 lasted about four and three months, respectively, the third lasted less than two months toward the end of 1998, and the last one for about 9.5 months in 1999. Of these, 686 events were located in or very close to the reservoir and 27 events were located ~10 km southeast of the reservoir (Fig. 2). Of the events in or very close to the reservoir, eight events were with $2.0 \leq M_L \leq 2.5$ and 20 events were with $1.5 \leq M_L < 2.0$. In this section, we report on those events that were located in or very close to the reservoir, and our criteria for selecting the events for analysis.

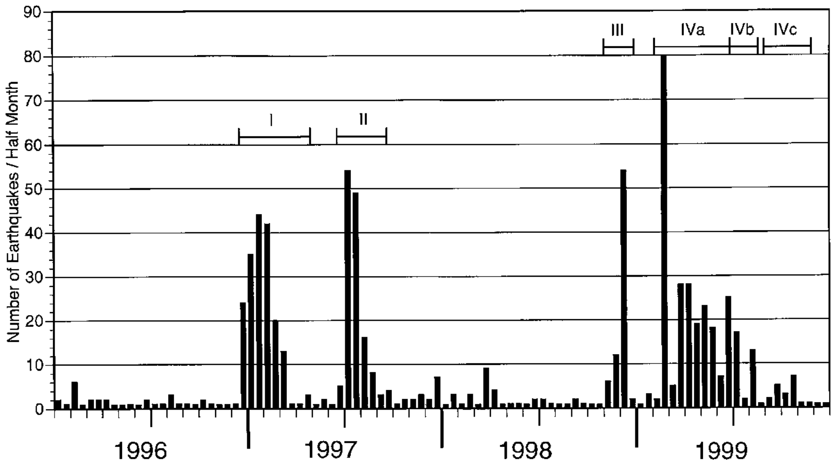

Figure 3. Semimonthly number of earthquakes in the Monticello Reservoir area from 1996 to 1999. Episodes of intense activity are shown by the horizontal bars.

Table 1
Episodes of Renewed Seismicity

Episode	No. of Events	From (mm/dd/yy)	To (mm/dd/yy)	Location in A	Depth (km)	Max Magnitude (M_L)
I	180	12/15/1996	04/20/1997	Center	0.8–2	2.0
II	128	06/20/1997	09/27/1997	Center	0.8–2	1.9
III	72	11/07/1988	12/26/1998	Center-East	<1.4	2.5
IVa	199	02/09/1999	06/22/1999	North	<2.0	2.4
IVb	45	06/23/1999	07/23/1999	South	<2.0	1.4
IVc	24	08/02/1999	11/27/1999	Center, North	<2.0	2.1

A majority of these earthquakes that were chosen for further analysis lie within a rectangular area, A, bounded by latitudes 34°19′ and 34°21′ north, and longitudes 81°18′ and 81°20′ west (Fig. 2). For a detailed analysis, we selected earthquakes lying within A and that satisfied the following location criteria: ERH < 0.5 km, ERZ < 0.5 km, RMS < 0.1 sec and quality B or better. From 15 December 1996 to 31 December 1999, 259 earthquakes satisfied the above criteria. The horizontal location error of most of these earthquakes was less than 300 m. As the epicentral distance to the nearest station was equal to or less than the focal depths and we used at least four *S*-phase readings (see, e.g., Gomberg *et al.,* 1990), our calculated depths are accurate to better than 500 m (the average ERZ was 340 m).

Figure 4a shows the spatial and temporal distribution of the seismicity in map view. Due to malfunctioning of station MR07 for parts of 1997, only 11% events lying within A met the quality criteria compared to 50% of 1998 and 73% of 1999. Episodes I and II were located in the same general area, roughly in the middle of A. Episode III, which occurred during November and December 1998, was located a few hundred meters to the east of the earlier episodes and at shallower depths (Figs. 4a and 4b). The seismicity in episode IVa (February to 22 June 1999) occurred 0.5 to 2.0 km to the north of the earlier episodes, moving ~0.5 km to the south of them between 23 June and 23 July 1999 (episode IVb). In the final episode (IVc), the seismicity occurred to the east and to the north (Fig. 4a). The seismicity in the first two episodes occurred at depths between ~0.8 and 2 km, becoming shallower in episode III (<1.4 km) and from near surface to 2 km in Episode IV (Fig. 4b). The migration of seismicity suggested the effect of pore pressure in inducing the recent seismicity (as was observed at Lake Jocassee [Talwani and Acree, 1984]). No deepening of seismicity was observed from its beginning in December 1996, suggesting that there was some hydrologic barrier at the bottom of the recent hypocentral area, preventing the pore pressure from diffusing to greater depths beneath the reservoir. We discuss the cause of this seismicity in a later section, but first we compare it with the seismicity that preceded it.

Comparison of Earlier and Recent Seismicity

Since the impoundment of Monticello Reservoir, about 10,000 earthquakes have been recorded, the majority of which occurred in 1978 and 1979. Using the same location quality criteria for comparison, there were 219 earthquakes occurring in box A between the time of impoundment in 1977 and the start of the renewed seismicity in December 1996 (Fig. 4c). The apparent alignment of epicenters at about 34°20′ (Figs. 2 and 4c) is an artifact of HYPO71 using the location of MR01 (Lat. 34°19.91′, Long. 81°17.74′) as a trial location. In various iterations the adjusted latitude 34°20′ gave least residue values for 16 recent and 18 earlier events. Comparison of the recent seismicity with that which occurred before shows that the earlier seismicity was very scattered, while the recent activity was concentrated along the NS zone (Fig. 4c). The recent seismicity also filled some of the seismic gaps in the earlier seismicity. Fig. 4d shows the location of earlier and new seismicity along NS cross-section. We note that the earlier seismicity was scattered, with the depths to almost 5 km, with the majority lying above 3 km. The recent earthquakes were shallower than about 2 km. From Figures 4c and 4d, we note that the recent events

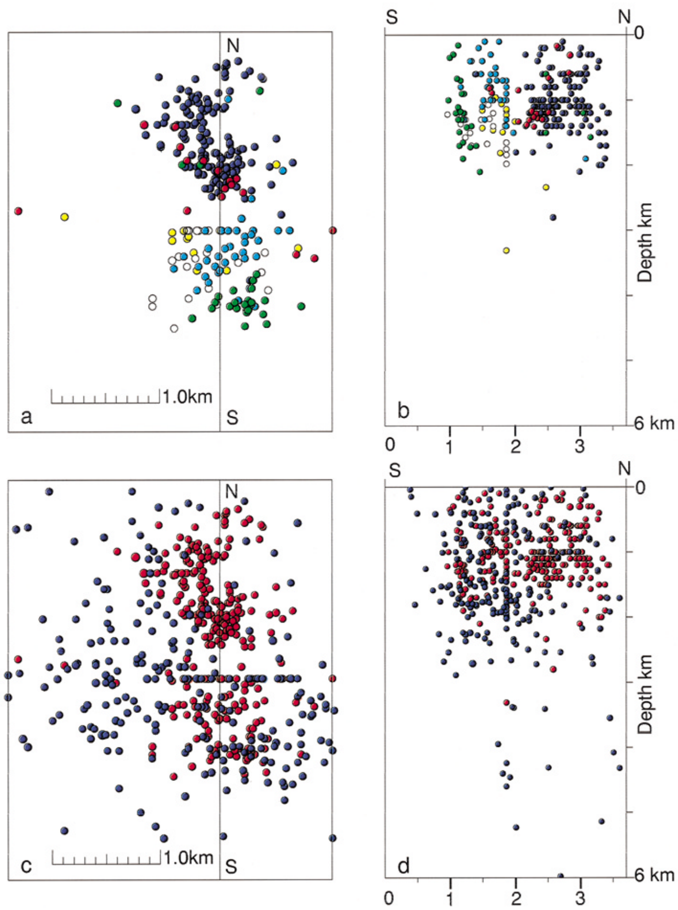

Figure 4. Figure 4a shows the different episodes of seismicity from 15 December 1996 to 31 December 1999 within box A in different colors. The color schemes for the earthquakes are the same as those in Figure 5. Figure 4b shows the same seismicity along a NS cross section. Figure 4c shows the locations of the seismicity in box A from the start of the reservoir impoundment in 1977 to 31 December 1999. Red dots show the seismicity from 15 December 1996 to 31 December 1999, and blue dots show the seismicity before 15 December 1996. Figure 4d shows these two groups of seismicity along a NS cross section.

mainly occurred in new regions, filling seismic gaps in the earlier seismicity.

Geology of the Epicentral Area

In the previous section we showed that the new bursts of seismicity filled seismicity gaps within regions of earlier seismicity. The paucity of earlier seismicity in the new hypocentral region suggested that it was surrounded by impermeable barriers where no open fractures existed, thus preventing diffusion of pore pressure from the surrounding regions. The new seismicity started in the middle of box A (Fig. 2) (episodes I and II), moved to shallower depths and to the east (episode III), and then migrated to the north and south (episode IV). During this time, the water level was very stable, lying between 128.17 and 129.54 m (South Carolina Electric and Gas Company, 1998, 1999, 2000), thus suggesting no causal relationship between the reservoir levels and seismicity.

Monticello Reservoir is located in a plutonic complex of Carboniferous age with complex and extremely heterogeneous geology. The area is characterized by high frequency gravity, magnetic and aeroradioactivity anomalies, and small outcrops. The spatial association of the outcrops with these high-frequency geophysical anomalies indicate that they are related, and the causative bodies are shallow and of limited extent (~1 to 2 km). The seismicity that followed impoundment showed excellent spatial correlation with the mapped geology and geophysical anomalies. It was located mainly in the migmatite units, and the intrusive granodiorites, granofels, and gneisses were largely aseismic. This observation suggested the presence of heterogeneous material properties and stress condition both laterally and with depth (Talwani and Acree, 1987). With that in mind, we examined the location of the current seismicity in relation to the mapped geology.

The following description of the geology is from South Carolina Electric and Gas Company (1977) and Secor *et al.* (1982) and summarized by Talwani and Acree (1987). The reservoir area is underlain by a complex series of interlayered and folded metavolcanic and metasedimentary rocks, all of which have been intruded by plutons of granitic to granodiorite composition. The pluton emplacement disrupted the foliation and compositional bedding planes of the intruded rocks. The plutonic rocks have been mapped as fingers, irregular zones, and as small to moderately large plutons with a generally concordant relationship with the host rocks.

The preimpoundment geologic investigation identified four distinct rock units underlying the reservoir (South Carolina Electric and Gas Company, 1977). These are migmatite, granodiorite, granofels, and Charlotte belt gneiss, and their location within box A is shown in Figure 5. The distribution of the surface rock types agrees with the geophysical anomalies and reflects the geology at the hypocenters (Talwani and Acree, 1987).

The migmatite unit contains a gradational assortment of migmatitic rock types, which generally are associated with mapped plutonic phenomena. *Migmatite,* as used herein, is defined by Turner and Verhoogen (1951) as consisting of two lithological elements intimately mixed: (1) country rock variously altered by metamorphism and metasomatism and (2) granitic material. In the reservoir area, three migmatite rocks were mapped: migmatite of gneissic composition with healed shears; contact breccia with angular and surrounded fragments strewn throughout a fine-grained granitic complex; and migmatites of granodioritic composition. The migmatites surround the plutons and extend hundreds of meters into the country rocks.

There are several granodiorite plutons in the reservoir

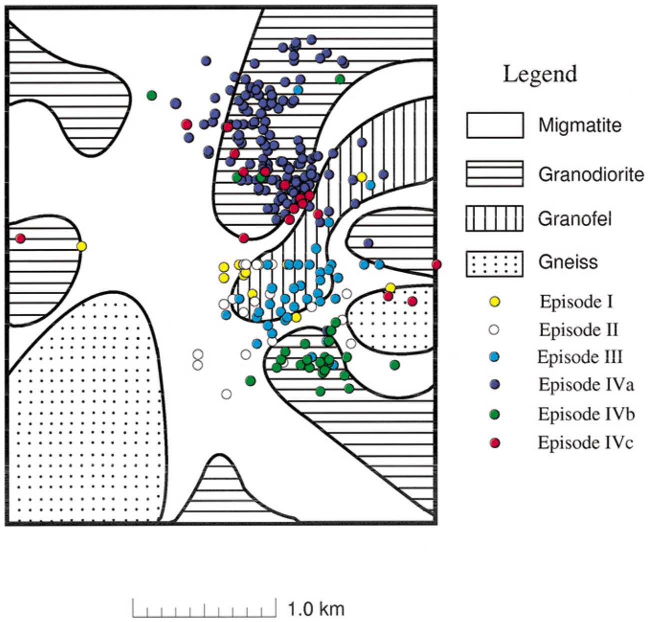

Figure 5. Geology and the new seismicity in the box A. Four basic types of lithology are shown, and the different episodes of seismicity are shown in different colors.

area. The granodiorites are exposed by high relief and occur in an irregular pattern across the reservoir area. Their precise boundaries are difficult to determine because of peripheral zone of migmatites. Gravity data suggest that granodiorites broaden at depth. They were exposed as large boulders and exhibited a fine, equigranular texture. Minor shearing was observed in one of the granodiorite plutons, at the location of Virgil C. Summer Nuclear Station. Four shear zones with a maximum observed displacement of about 2.1 m cut across a granodiorite-migmatite complex (Wagener, 1977). Microbreccia of granodiorite in the shear zone contained hydrothermally derived, undisturbed 45 m.y. old zeolites. The granofels unit contains fine-grained rocks of granitic texture with slight foliation. Rocks of Charlotte belt gneiss occur in the southwest corner and the central eastern part of box A.

The seismicity that followed impoundment in 1977–1978 was located in the more heavily fractured migmatite units bordering the granodiorite plutons and the granofels (Talwani and Acree, 1987).

Comparison of Seismicity With Geology

The hypocentral locations in box A for the various episodes are compared with the detailed geology in Figure 5. We note that episodes I and II are located in the middle of the box and near the southern contact of the granofels with migmatite. These events occurred between depths of 0.8 and 2.0 km. In 1978 and 1979, earthquakes occurred in the same epicentral area as that of episodes I and II (Talwani and Acree, 1987), but were all shallower than 1 km. In the third episode the seismicity migrated to shallower depths (Fig. 4b) and occurred in the granofels (Fig. 5). In episode IV, the earthquake clouds to the north and south covered the whole depth range from near surface to about 2 km compared to a shallower episode III and deeper episodes I and II (Fig. 4b). In episode IVa seismicity was located in granodiorite to the north, and episode IVb to the south (Figs. 4b, 5). Episode IVc was scattered, located mainly in granodiorites and migmatites.

Seeburger and Zoback (1982) found significant differences in the state of natural fracturing in the two wells drilled to depths ~1 km and located to the west and south of the Monticello Reservoir, and 5 km from each other (Fig. 2). The fracture density in the two wells varied greatly, both laterally and vertically. These observations and stress measurements in the two wells (Zoback and Hickman, 1982) further confirmed that the Monticello Reservoir area shows great heterogeneity both laterally and vertically in lithology, fracture distribution, and stress accumulation. We next address the possible cause of the current seismicity.

Mechanism of the Seismicity

Following Mogi (1988), we examined the time series for the earthquake episodes in light of rock fracture experiments in the laboratory. He found that when a constant load is applied to heterogeneous rock specimens, the frequency curve of acoustic emission on a semilogarithmic graph is linear. He found that the frequency (n) of acoustic emission events under a constant stress can be expressed as a function of time (t) as follows:

$$n = n_0 \, e^{-\lambda t} \tag{1}$$

where n_0 and λ are constants. The decay constant λ increases with an increase in stress. In our case, theoretical calculations (Chen and Talwani, 2000) and lack of change in lake levels suggest that the seismicity is not due to the rise in lake levels, or equivalently application of additional stress, but is associated with increases in pore pressure. Correspondingly, we associate the log-linear behavior of the frequency curve with changes in pore pressure. Strength changes, ΔS, associated with pore pressure changes, ΔP, can be expressed as:

$$\Delta S = \mu(\Delta\sigma_n - \Delta P) - \Delta\tau \tag{2}$$

where $\Delta\sigma_n$ and $\Delta\tau$ are the changes in the normal and shear stresses, and μ is the coefficient of friction. Negative ΔS signifies weakening. An increase in the frequency of earthquakes is interpreted as being because of an increase in pore pressure and thus decrease in strength ΔS. When there is no further increase in pore pressure (due to an external cause), it diffuses and equilibrates, triggering a decreasing number of earthquakes over a growing volume. In short, an increase in seismicity on the plot of log n vs. time is interpreted as being due to increasing pore pressure, and a decrease is interpreted as being due to equilibration. During the equilibration stage, pore pressure diffuses through the fractures, triggering an outward migrating cloud of seismicity. The rate of equilibration of pore pressure is then attributed to the hydraulic diffusivity (or equivalently, the permeability) of the fractures. Faster equilibration is associated with a faster decay in seismicity (higher λ), and it occurs in rocks with higher permeability and vice versa.

Based on these arguments, we examined the frequency curve of the seismicity plotted on a semilogarithm scale (Fig. 6). For each of the four episodes, we note a rapid period of increase in seismicity, which we interpret as being a result of a rapid increase in pore pressure. The rate of decay, however, is different, being rapid for the first three episodes and slow for the fourth. We also note that the first three episodes were primarily associated with seismicity in the granofels and to a small extent, surrounding migmatites, whereas the fourth was associated with the granodiorites. We also note that the epicentral area grew for a longer time and covered a larger volume in episode IV than for the earlier episodes. We attribute these differences to lower hydraulic diffusivity and larger available volume of previously untapped granodiorites compared to the granofels that hosted episodes I–III. By the end of 1999, seismicity reduced to background levels, indicating that the pore pressure diffusion was complete in these new regions.

Discussion and Conclusions

A new burst of seismicity occurred nearly 20 years after the impoundment of Monticello Reservoir, and at a time when there were no changes in reservoir water level. Detailed analysis of this new seismicity, comparison with the seismicity that preceded it, and the detailed geology of the reservoir area suggest the following scenario for their occurrence.

Monticello Reservoir is located in an area of great geological heterogeneity. Due to construction of the Virgil C. Summer Nuclear Station, very detailed geological mapping and shallow drilling revealed that the study area consisted of small ~1 to 2 km deep and less than a few km wide intrusive granofels, granodiorites, and Charlotte belt gneiss bodies surrounded by heavily fractured migmatites. Networks of fractures with different orientations and hydraulically sealed from each other were discovered in Monticello Well #2 (Fig. 2; Seeburger and Zoback, 1982).

The presence of zeolite in the reservoir area was observed by detailed mapping (South Carolina Electric and Gas Company, 1977; Wagener, 1977) and in the cores from the observations wells (Talwani and Acree, 1987). Zeolites were formed in granodiorite units (Wagener, 1977). Undisturbed zeolites in shears showing ~2.1 m displacement were dated at ~45 m.y., suggesting the absence of faulting since then. Zeolites are a large group of hydrous aluminosilicates analogous in composition to feldspars, and have formed due to water-rock interactions under low-grade metamorphic conditions (Wilkin and Barnes, 1998). Due to their open and hydrated structures, they have lower specific gravity (2.0 to 2.2 g/cm^3) compared to feldspars (2.6 to 2.7 g/cm^3) (Ragnarsdóttir, 1993).

Due to a tight network of close-in seismic stations, hypocenters were located with an accuracy of better than 500 m. Thus it was possible to compare hypocentral locations of the new seismicity with the local geology. Since its inception in 1977, seismicity near Monticello Reservoir occurred mainly at depths shallower than 2 km (Talwani and Acree, 1987), suggesting greater availability of fractures at these depths. Earlier seismicity (1977–1996) mainly occurred in migmatites, which have a higher density of fractures and surround the intrusions of granodiorite and granofels.

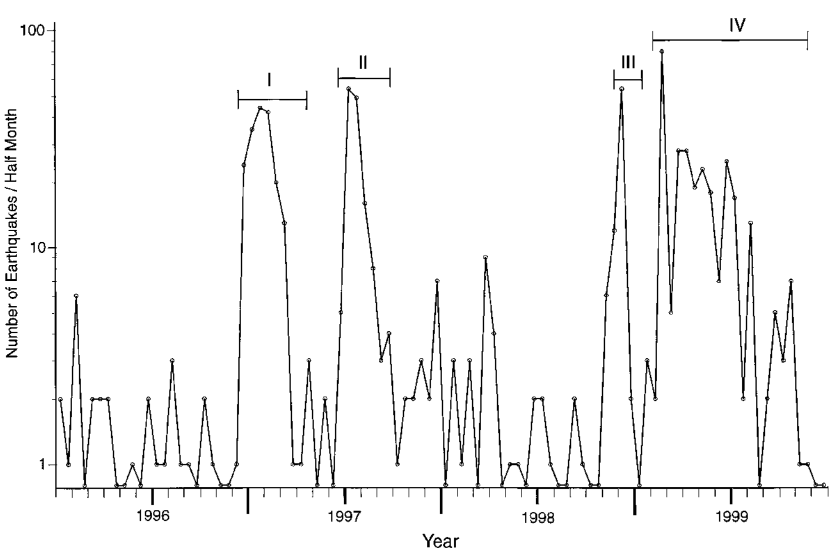

Figure 6. Semimonthly number of earthquakes at Monticello Reservoir from 1996 to 1999 shown on a semilogarithmic graph. Different episodes are shown by the horizontal bars.

The four episodes of seismicity since 15 December 1996 occurred in a new volume. Episodes I and II started at depths of 0.8 to 2 km in granofel bodies and the surrounding area. Episode III occurred more than a year later and was also located in granofels to the east of the first two episodes and at shallower depths (from the surface to $\sim$1.4 km deep). The seismicity in episode IV migrated to the north and south and occurred in granodiorites. In each of the four episodes, there was at least one earthquake with magnitude $M_L \geq 2.0$ (Table 1).

From these observations, we speculate that the new hypocentral regions were isolated from the surrounding areas by sealed fractures containing zeolites, preventing pore pressure increase due to reservoir impoundment from diffusing into the sealed regions. After 20 years, and under about 3 bars head, water caused both dissolution and hydration of zeolites. Dissolution resulted in the replacement of zeolites with higher density precipitates (i.e., occupying less space), thus increasing the permeability of the fractures. Hydration resulted in swelling of the remaining zeolites and consequently the weakening of the fractures. Thus, 20 years of reaction with water led to the reopening and weakening of the zeolite-filled fractures. The reopened fractures became the conduits for excess pore pressure (due to the reservoir impoundment) to diffuse to a previously aseismic region. The increase in pore pressure further weakened the fractured rocks and induced earthquakes. The fractures in granofels and the surrounding rocks were first opened and triggered episodes I and II. More than a year later, pore pressure migrated to shallower regions within granofels and induced episode III. In 1999, pore pressure further migrated to the north and south of the granofels in two bodies of granodiorites, inducing Episode IV. During this period, no migration of seismicity to the deeper space was observed, suggesting an absence of open fractures at the bottom of the new hypocentral region.

Mechanism of the Renewed Seismicity

To infer the mechanism of these episodes, we present a speculative scenario based on Mogi's (1988) model for the Matsushiro earthquake swarm. This is illustrated in Figure 7, where we present the seismicity in the four episodes on a semilogarithmic graph. We interpret the changes in the frequency (Fig. 7a) to be associated with pore pressure changes (Fig. 7b).

For each of the four episodes, two stages with different temporal and spatial patterns are observed. For episode I, in the first stage, there was a rapid increase in seismicity (Fig. 7a); we interpret this to be associated with the rapid buildup of pore pressure (Fig. 7b). In the second stage, the seismicity rate decayed (Fig. 7a); we interpret this stage to be associated with the equilibration of pore pressure (Fig. 7b). We speculate that episode II occurred in a different set of fractures, probably requiring increase in pore pressure in a new volume (stage one associated with increased seismicity) before equilibration of pore pressure (seismicity decay). A

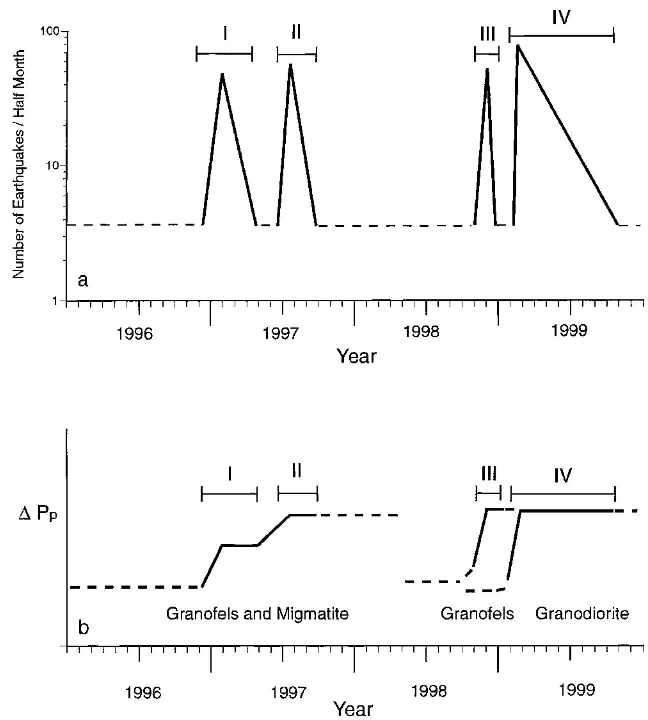

Figure 7. Speculative association of seismicity (Figure 7a) in the four episodes (horizontal bars) with changes in pore pressure ΔP (Figure 7b). Each episode is associated with two stages, an increase in seismicity, interpreted to be due to an increase in pore pressure; and a decrease in seismicity, interpreted to be associated with the diffusion and equilibration of pore pressure. The lithology associated with each of the episode is also shown in Figure 7b.

similar pattern persisted for episodes III and IV. The seismicity decay rate differed in different episodes, faster in the first three episodes which occurred mainly in granofels, and slower in episode IV which was mainly located in granodiorites (Fig. 7a and 7b). The slower decay rate of seismicity in episode IV suggests a lower hydraulic diffusivity (or equivalently lower permeability). We associate the longer duration of the seismicity decay in episode IV with larger volume of the granodiorites.

If our speculative model for the cause of the renewed seismicity is correct, we can anticipate seismicity within other (hitherto aseismic) plutons of granodiorites and granofels, including the site of the Virgil C. Summer Nuclear Station.

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References

Chen, L., and P. Talwani (2000). Mechanism of initial seismicity following impoundment of the Monticello Reservoir, South Carolina, *Bull. Seism. Soc. Am.* (submitted).

Gomberg, J. S., K. M. Shedlock, and W. Roecker (1990). The effect of *S*-arrival wave times on the accuracy of hypocenter estimation, *Bull. Seism. Soc. Am.* **80,** 1605–1628.

Lee, W. H. K., and J. C. Lahr (1972). HYPO71: A computer program for determining hypocenter, magnitude, and first motion pattern of local earthquakes, *U. S. Geol. Surv. Open-File Rept. 75-311,* 113 pp.

Mogi, K. (1988). The mechanism of the occurrence of the Matsushiro earthquake swarm in Central Japan and its relation to the 1964 Niigate earthquake, *Tectonophysics* **159,** 109–119.

Pujol, J. (1988). Comments on the joint determination of hypocenters and station corrections, *Bull. Seism. Soc. Am.* **78,** 1179–1189.

Pujol, J. (1992). Joint hypocentral location in media with lateral velocity variations and interpretation of the station corrections, *Phys. Earth Planet. Interiors* **75,** 7–24.

Ragnarsdóttir, K. V. (1993). Dissolution kinetics of heulandite at pH 2–12 and 25°C, *Geochim. Cosmochim. Acta* **57,** 2439–2449.

Ratchkovsky, N. A., J. Pujol, and N. N. Biswas (1997). Relocation of earthquakes in the Cook Inlet area, South Central Alaska, using the joint hypocentral determination method, *Bull. Seism. Soc. Am.* **87,** 620–636.

Secor, D. T., Jr., L. S. Peck, D. M. Pitcher, D. C. Prowell, D. H. Simpson, W. A. Smith, and A. W. Snoke (1982). Geology of the area of induced seismicity activity at Monticello Reservoir, South Carolina, *J. Geophys. Res.* **87,** 6945–6957.

Seeburger, D. A., and M. D. Zoback (1982). The distribution of natural fractures and joints at depth in crystalline rock, *J. Geophys. Res.* **87,** 5517–5534.

South Carolina Electric and Gas Company (1977). Virgil C. Summer Nuclear Station, Final Safety Analysis Report, Volume II, 520 pp.

South Carolina Electric and Gas Company (1998). Parr Hydroelectric Project F.E.R.C. Project No. 1894, Routine Surveillance Report No. 93, January 1, 1997 to December 31, 1997.

South Carolina Electric and Gas Company (1999). Parr Hydroelectric Project F.E.R.C. Project No. 1894, Routine Surveillance Report No. 94, January 1, 1998 to December 31, 1998.

South Carolina Electric and Gas Company (2000). Parr Hydroelectric Project F.E.R.C. Project No. 1894, Routine Surveillance Report No. 95, January 1, 1999 to December 31, 1999.

Talwani, P. (1997). On the nature of reservoir-induced seismicity, *Pure Appl. Geophys.* **150,** 473–492.

Talwani, P., and S. Acree (1984). Pore pressure diffusion and the mechanism of reservoir induced seismicity, *Pure Appl. Geophys.* **122,** 947–965.

Talwani, P., and S. Acree (1987). Induced seismicity at Monticello Reservoir: A case study, *U.S. Geol. Surv. Final Tech. Rept.* 271 pp.

Talwani, P., L. Chen, J. Garner, and R. Cannon (1997). South Carolina Seismic Network Bulletin, Volume VI, 31 pp.

Talwani, P., L. Chen, L. Gomide, and R. Cannon (1998). South Carolina Seismic Network Bulletin, Volume VII, 31 pp.

Talwani, P., L. Chen, M. Dasgupta, and R. Cannon (1999). South Carolina Seismic Network Bulletin, Volume VIII, 30 pp.

Talwani, P., L. Chen, and R. Cannon (2000). South Carolina Seismic Network Bulletin, Volume IX, 35 pp.

Turner, F. J., and J. Verhoogen (1951). Igneous and metamorphic petrology, McGraw-Hill, New York, 294–297.

Wagener, H. D. (1977). Zeolites as indicators of time of latest movement of Piedmont faults: the Virgil C. Summer Nuclear Station, the Geological Society of America, Southeastern Section 26th Annual Meeting, Abstracts with Programs 9, 192–193.

Wilkin, R. T., and H. L. Barnes (1998). Solubility and stability of zeolites in aqueous solution. I. Analcime, Na-, and K-clinoptilolite, *American Mineralogist* **83,** 746–761.

Zoback, M., and S. Hickman (1982). In situ study of the physical mechanisms controlling induced seismicity at Monticello Reservoir, South Carolina, *J. Geophys. Res.* **87,** 6959–6974.

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