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Booming Plutons: Source of microearthquakes in South Carolina

Donald Stevenson[1], Abhijit Gangopadhyay[2], and Pradeep Talwani[2]

[1]Westinghouse Savannah River Company, Aiken, South Carolina

[2]Department of Geological Sciences, University of South Carolina, Columbia, SC 29208

Abstract

Loud, shallow microearthquakes (M < 3.0), occurring in the vicinity of granitic plutons represent a different category of seismicity compared to other recognized seismic sources in South Carolina. We demonstrate this difference by comparing the locations of microearthquakes in the vicinity of three granitic plutons in South Carolina, with the results of two-dimensional numerical modeling and analytical studies. The less rigid plutons embedded in more rigid country rock, were loaded by ambient tectonic plate stresses along the direction of maximum horizontal compression. The results of modeling showed that regions of computed high stresses lie on the periphery of the plutons, and coincide with both the observed locations of seismicity, and with lobes of elevated stresses obtained by analytical calculations for a weak pluton subjected to a homogenous stress field. The amplitude of the modeled stresses appears to be a function of the shape and size of the pluton.

Introduction

The earthquake history of South Carolina is dominated by the catastrophic Charleston earthquake of August 31, 1886. To date, the Middleton Place Summerville Seismic Zone (MPSSZ), where this earthquake occurred, remains the most seismically active region in South Carolina. Besides MPSSZ, earthquakes have been located in Bowman Seismic Zone (BSZ), around reservoirs, and occasionally ($M \leq 3$) in other parts of South Carolina (Tarr et al., 1981). This "other" seismic activity, generally concentrated within the Piedmont and upper Coastal Plain physiographic provinces (Figure 1), is the subject of this paper.

The Piedmont province is divided into a number of northeast trending lithotectonic belts which continue southeast under the Coastal Plain sediments (Daniels et al., 1983). Several small granitic batholiths emplaced within broad regions of the Piedmont also occur under the Coastal Plain sediments. Intriguingly, many of the small earthquakes mentioned above were located in the vicinity of these granitic plutons. A spatial and possible causal association of mafic plutons with earthquakes was first suggested in the 1970s (see for e.g. Long, 1976; Long and Champion, 1977; Kane, 1977). Theoretical studies (e.g. Campbell, 1978) suggested possible mechanisms, but the pre-instrumental locations were inadequate to demonstrate causal associations.

The installation of the South Carolina Seismic Network (SCSN) in the mid-1970s provided accurate examples of spatial correlation of microearthquakes with granitic plutons, which are less rigid than the surrounding country rocks. These earthquakes which occur on the intrusive's periphery are in general shallow, as evidenced by their booming noises. The objective of this study was to demonstrate, using two-dimensional numerical modeling, a causal association of the granitic plutons with these earthquakes, as was theoretically postulated by Campbell (1978). We demonstrate a possible causal association with three examples from South Carolina; Rion and Newberry plutons in the Piedmont, and Neeses pluton in the Coastal Plain, where adequate seismological and geophysical data (to define their periphery) are available (Figure 1). Microearthquakes were instrumentally located in the vicinity of each of these plutons. Low-level ($M_d < 2.0$)

events with depths ranging from about 1 to 4 km and occurring from 1996 – 2003, were located near Rion using the Monticello Reservoir network ~10 km away (M.R. in Figure 1). These depths are not well constrained. Swarms of earthquakes near the Newberry pluton (1982 – 1984) were studied by Rawlins (1986) using the Monticello Reservoir network and portable seismographs located in the epicentral area. Over a hundred events with magnitudes from less than 0 to 2.6, with well-constrained depths were found to lie in the top 2 km. Three felt earthquakes with M 1.9 to 2.5 and occurring in 1992 – 1993 were located near the Neeses pluton using stations of the South Carolina Seismic Network. Their depths are not well constrained.

Next, we describe the simple 2-D mechanical models to determine the locations of anomalous stress build-up for the inferred pluton geometry in the current stress field, and compare the locations of modeled stress accumulation with the location of current seismicity to demonstrate a causal association. The results of this study show that these earthquakes represent a third category of earthquakes in South Carolina.

Distinct Element Modeling using UDEC

Two-dimensional numerical modeling of stress accumulation was carried out using the Distinct Element Method using a program called Universal Distinct Element Code (UDEC) written by Itasca Consulting Group, Inc., Minneapolis, MN (Version 3.1, 1999) (For details and applicability of this method to various geologic situations see Gangopadhyay et al., 2004). For computational convenience of modeling, the plutons in each model were rotated 30° clockwise, so that, the direction of maximum horizontal compression, S_{Hmax} lies along the x-axis (Figures 2 and 3). The regional S_{Hmax} is oriented N60°E in the area (Talwani, 1982; Zoback, 1992). The block assembly, which includes the pluton embedded within the country rock (Figure 3), was subjected to a horizontal compressive force along the x-axis whose value was derived using the differential plate velocity of 2 mm/year measured from geodetic studies (1 – 2 mm/year (Dixon et al., 1996), and 1.7 ± 0.9 mm/year (Gan and Prescott, 2001) for the eastern North American stable continent, and ~2 mm/year (Trenkamp and Talwani, 2005) for the Charleston, South Carolina region). A displacement boundary condition was applied to the model by keeping the left boundary of the model fixed and allowing the right boundary to move at 2mm/year.

Input parameters for the model calculations include elastic moduli, density of the plutons and the country rocks surrounding them, friction angle, normal and shear stiffnesses, and cohesion of the pluton boundaries. Some of these parameters are based on laboratory studies and are described in detail in Gangopadhyay et al. (2004). We have assigned the mean friction angle for granite to be 33° and following Rosso (1976), we used 133 GPa/m and 100 GPa/m respectively for the normal and shear stiffnesses of granite. In all of our models we have assigned no cohesion to the pluton boundaries.

Three Examples from South Carolina

The granite and quartz monzonite, Rion pluton, covering an area of ~50 km^2, intruded along the border of two lithotectonic belts in the Piedmont (see Secor, 1980 and references therein). Around most of its circumference, the Rion pluton is surrounded by a screen of country rock. The outline of the Rion pluton is based on surface geology and an isolated gravity low, and is shown on the Bouguer gravity map (Figure 2a). A 575 m deep core taken from the east-central part of the Rion pluton, had an average density of 2.62 g/cm^3 (Costain et al., 1979). This value was used in our model computations. For all three plutons, an average P-wave velocity (V_p) of 5.8 km/s, based on laboratory data (Press, 1966), and a V_p/V_s value of 1.73 was used. Correspondingly, the computed values of bulk and shear moduli for Rion pluton are 48.93 GPa and 29.40 GPa respectively. Rawlins (1986) reported the results from analyses of rock samples from different lithotectonic belts of South Carolina. The felsic gneiss that comprised the country rocks in the region have a density of ~2.71 gm/cm^3, and V_p, 6.2 km/s (Press, 1966). For these values which were used for the country rocks surrounding all the plutons, the bulk and shear moduli were found to be 57.87 GPa and 34.73 GPa respectively. To allow for contrast in material properties between the pluton and the host rock to be also included in the modeling, a block with an area of 7.2 km × 9.4 km surrounding the Rion pluton was chosen (Figure 3a).

The Newberry pluton is an irregularly shaped, generally elongated body lying roughly parallel to the northeast regional strike and consists of finely grained homogenous granite in its central part. Superimposition of detailed Bouguer gravity, aeromagnetic, and radiometric maps (Rawlins, 1986) indicates that it covers a nearly elliptical region of ~50 km^2. Figure 2b shows the inferred outline of the Newberry pluton plotted on the aeromagnetic anomaly map. For modeling, we took an area of 8.3 km × 10.5 km which includes the pluton and the surrounding rocks (Figure 3b). The average density, of rocks from this pluton, 2.64 g/cm^3 (Rawlins, 1986), was used in model computations. The computed values of bulk and shear moduli for the Newberry pluton were 49.30 GPa and 29.62 GPa respectively.

Evidence for the existence of the Neeses pluton under the Coastal Plain sediments was initially based on a circular -45 mGal Bouguer gravity low near the town of Neeses

(Talwani et al., 1975). Granitic rock was encountered at a depth of ~263 m in a well drilled near the center of this gravity low, and its density was found to be ~2.65 g/cm^3 (Speer, 1982). Using this value, the bulk and shear moduli were computed to be 49.50 GPa and 29.73 GPa respectively. The model geometry was based on a detailed Bouguer gravity map (Madabhushi and Talwani, 2000 personal comm.; Figure 2c). The surface dimension of the pluton is ~200 km^2 and including the modeled host rock surrounding it, the modeled area represents 28.5 km × 18.2 km (Figure 3c). The next section describes the modeling results.

Model results and their analysis

The outputs from the modeling were analyzed in terms of the resulting shear stresses in the modeled blocks in response to an applied tectonic loading time, (i.e. in the computer program) of one or two days. We assume temporal stationarity of the locations of modeled stresses so as to compare them with the locations of seismicity. For each case the results are presented in two ways. First, the shear stress values obtained from the 2-D model are superimposed on a map showing an outline of the pluton and the location of seismicity (Figures 3a – c). Shear stresses (τ_{xy}) were obtained at each node of the model mesh, and positive and negative values are associated with counter-clockwise and clockwise rotation respectively. Their absolute values are instructive and determine potential seismogenic regions. They were contoured with a contour interval of 1 N/m^2. Next, the outline of the pluton is compared with an equivalent geometric shape, ellipse for Rion and Newberry plutons and a circle for the Neeses pluton. Then the analytically derived lobes of large stresses around the simple geometries (Campbell, 1978) are compared with the locations of seismicity. We next present these results in detail. The pluton outlines have been superimposed on the contoured shear stresses for convenience of comparison.

For the Rion pluton, the larger shear stresses (±3 to ±4 N/m^2) seen at the outer edges of the surrounding block are artifacts of boundary effects in the calculations and are ignored (Figure 3a). Away from these edges, elevated shear stresses were observed on the southwestern (3 to 5 N/m^2), western (±3 to ±5 N/m^2), and northeastern (-3 to -5 N/m^2) boundaries of the pluton, compared to those inside the pluton (0 to ±1 N/m^2). All these increased stresses are concentrated in very small regions on the periphery of the pluton.

For the Newberry pluton, shear stresses (±3 to ±4 N/m^2) were observed near the outer edges of the surrounding block, and have been ignored because they are artifacts of boundary effects in the calculations (Figure 3b). Away from these block edges the shear stress is elevated on the northeastern (3 to 5 N/m^2), southern (3 to 6 N/m^2), southeastern (-3 to –5 N/m^2), and southwestern (3 N/m^2) boundaries of the pluton. Inside the pluton showed almost no accumulation of shear stress (0 to ±1 N/m^2).

As the Neeses pluton is larger than the other two, and thus needed more tectonic loading time to obtain noticeable shear stress build-up, the model was run for a loading time of two days, twice that for the other two. Shear stresses (7 to 9 N/m^2) seen at the outer edge of the surrounding block are artifacts of boundary effects in the calculations and are ignored (Figure 3c). Away from this edge the shear stress is highest on the east-northeast boundary of the pluton (2 to 4 N/m^2) compared to 0 to 1 N/m^2 inside the pluton.

Discussions and Conclusions

Geologically, we would expect that the contact zone between an intrusive pluton and the country rock would be weaker than either two and a potential location of seismicity. However, the onset and location of this seismicity depends on the shape, size, and elastic properties of the pluton. Examination of seismicity in the vicinity of these plutons in South Carolina and the results of modeling (Figures 3 a – c) show a remarkable correlation. The instrumental seismicity located on the southwestern boundary of the Rion pluton, the northeastern periphery of the Newberry and Neeses plutons occurs in locations of elevated shear stress from modeling results (Figures 3 a – c). Analytical results of stress concentration due to circular and elliptical intrusions, both for those that are stiffer and weaker than the host rock, were presented by Campbell (1978) in the form of contours around and inside the intrusions. In the case of a weak intrusion he showed that the largest stresses, several times the regional stress, occurred in small pockets in the host rock just outside the intrusion (broken circles in Figures 4 a - c) – the potential locations for seismicity. Figures 4 a – c show that the shapes of the Rion and Newberry plutons can be approximated by ellipses, and that of Neeses by a circle. It also shows the location of seismicity (shaded area), is coincident with one of the lobes of elevated stresses (broken circles) for these shapes, based on the analytical results of Campbell (1978).

In conclusion, a comparison of Figures 3 and 4 suggests that the seismicity occurs on the periphery of the plutons, and its location coincides with modeled regions of high stresses, and with analytical calculations of Campbell (1978). This observation suggests that the seismicity is associated with stress amplification around the plutons resulting from a rigidity contrast with the surrounding rocks.

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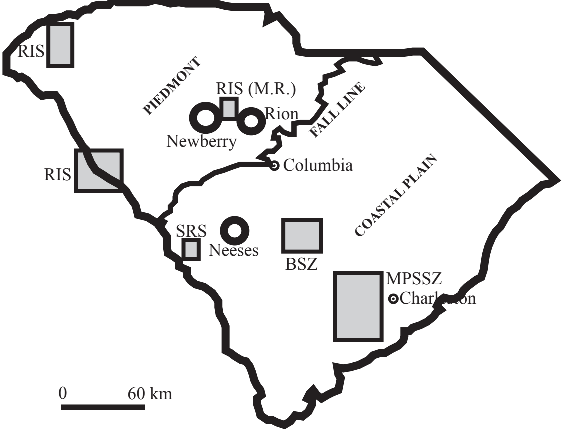

Figure 1: Map of South Carolina showing active seismogenic regions (shaded regions). Reservoir-induced seismicity (RIS). MPSSZ - Middleton Place Summerville Seismic Zone, BSZ - Bowman Seismic Zone, SRS - Savannah River Site. M.R. shows the location of Monticello Reservoir seismic network. Open circles represent the locations of the Rion, Newberry, and Neeses plutons.

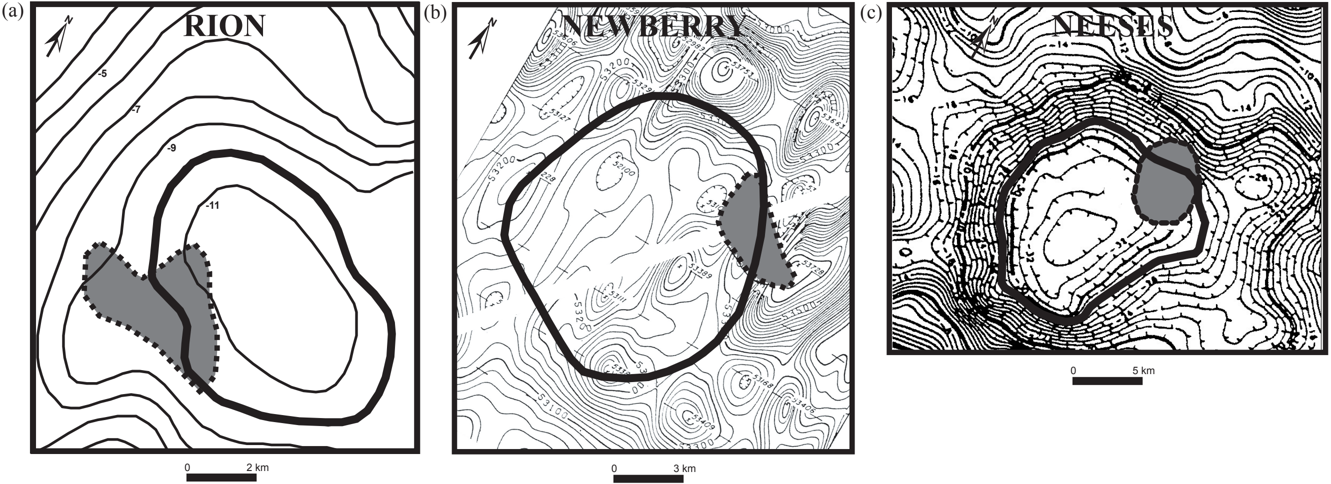

Figure 2: Outlines of the plutons (solid thick contours) and instrumental seismicity (shaded area) for the Rion (a), Newberry (b), and Neeses (c) plutons. The outlines of the Rion and Neeses plutons are shown on Bouguer anomaly maps (c.i. 1 mGal), and that of the Newberry pluton is shown on an aeromagnetic map (c.i. 100 nT). Details of the seismicity are given in the text.

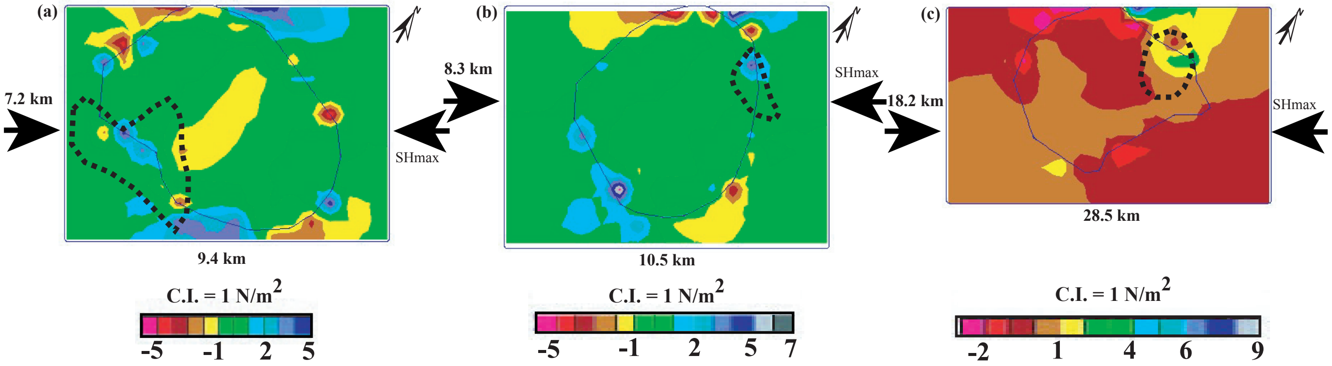

Figure 3: Shear stress contours superimposed on the outlines (thin lines) for **(a)** Rion **(b)** Newberry and **(c)** Neeses plutons. The area enclosed by the dotted black line in each panel represents the instrumental seismicity in the region. The direction of S_{Hmax} used in the models is shown by bold arrows and the plate velocity in each case along that direction was 2 mm/yr. The dimensions of the blocks in each case are also indicated.

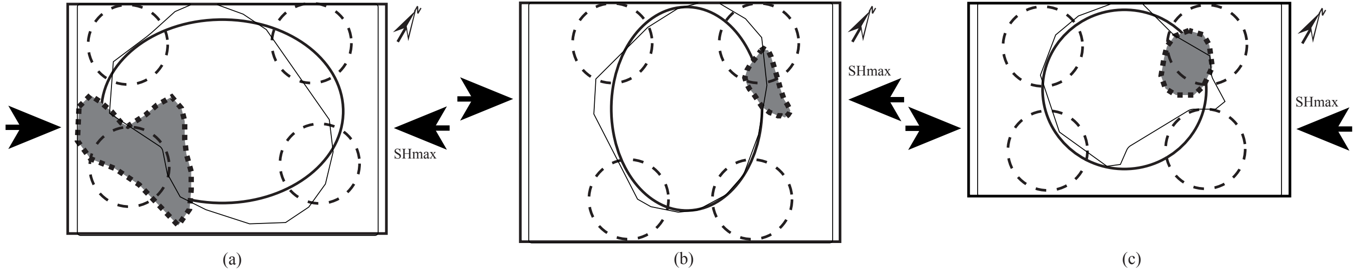

Figure 4: Shapes of the Rion (a) and Newberry (b) plutons are approximated by an ellipse and the Neeses pluton (c) by a circle (darker black lines). Broken circles show lobes of elevated stress according to Campbell (1978), and shaded areas show locations of seismicity. The direction of S_{Hmax} used in the models is shown by bold arrows.