2001- 2002 Upper Three Runs Sequence of Earthquakes at the Savannah River Site, South Carolina

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ABSTRACT

On October 08, 2001 a small felt earthquake (*mbLg* 2.60) occurred near Upper Three Runs Creek in the north central area of the Savannah River Site, South Carolina. It was located at 33.32° N, 81.67° W with a focal depth of 3.9 ± 0.8 km and an origin time of 00:23:01.12 UTC. Seven very small aftershocks ($M_D \leq 1.4$) followed the main event with the last one occurring March 06, 2002. All activity occurred within a small area of 6.0-6.5 km². Further analysis of collected data indicates a correlation of this low level seismic activity with a small northwest trending structure observed in detailed gravity and magnetic data. Both single event and composite focal mechanisms were derived using local and regional stations. Results indicated predominantly dip-slip motion along a fault striking NNW at 335° and dipping 41° to the southwest. A 3D plot of the eight hypocenters clearly defines a fault plane nearly analogous to that obtained from the focal solutions.

The Upper Three Runs series of events is another example of a separate class of earthquakes that occur within the central Piedmont and upper Coastal Plain of South Carolina. The “Upper Three Runs” sequence of events demonstrates that shallow intersections of structures interpreted from potential field data can be the foci for localized stress concentrations where microearthquake activity ($M \leq 3.0$) can occur. These earthquakes are attributable to small scale faults associated with pockets of relatively high stress concentrations and are generally accompanied by loud noises. Their shallow depth and small epicentral area suggest that these earthquakes are extremely localized and are not attributable to any large scale regional features.

INTRODUCTION

On October 07, 2001, at 08:23 p.m. (EDST) (October 8, 00:23 UTC) a small felt earthquake (*mbLg* = 2.60) occurred south of Aiken, South Carolina within the boundary of the US Department of Energy Savannah River Site (SRS). It was described by witnesses in the immediate epicentral area and nearby towns of New Ellenton, Jackson, and Williston as a loud thump. Seven instruments of the SRS seismograph network recorded the event, as did eight stations in the South Carolina Seismic Network (SCSN). A nearby station installed in Silver Bluff High School as part of an educational outreach program known as The South Carolina Earth Physics Project (SCEPP), also recorded the event. The best locations were obtained using data from the seven stations of the SRS network, whose epicentral distances ranged from 1.4 to 30 km.

Since the installation of the SRS seismic recording network in 1976, three small earthquakes previous to this event have occurred within the boundaries of SRS. They include the June 09, 1985 magnitude 2.6 event (Talwani et al., 1985), the magnitude 2.0 August 05, 1988, and the magnitude 2.5 May 17, 1997 events. Obvious features of this latest activity that differentiate it from previous SRS on-site events include its location and the number of aftershocks. The earlier events were concentrated within a relatively small cluster near the south-central area of SRS and had no associated aftershocks. The current activity is also confined to a relatively small area, however, this latest cluster is shifted to the north-central region of the SRS approximately 10 km north of previous activity (Figures 1 and 2). Also, seven aftershocks have been associated with the October 08, 2002 shock. The largest aftershock had a local duration magnitude (M_D) of 1.4 and the smallest an M_D of 0.1.

Extensive geological and geophysical studies have been performed at the SRS for more than 50 years. There are quite possibly more detailed geologic subsurface data available for the 795km^2 area of the SRS than any other area in the eastern U.S. Most of the available geologic information is concentrated on the relatively shallow Coastal Plain sediments underlying the SRS. An exception to this however, is a data set containing over 270 km of modern seismic reflection lines covering much of SRS processed to recover reflections from geologic structures below the Coastal Plain and above the upper mantle. Much of these data have been interpreted and reported by Domoracki (1995). Detailed gravity and aeromagnetic data are also available for the region. These relatively detailed subsurface data were used to identify possible seismogenic features associated with this latest low level Upper Three Runs seismic activity.

SERIES OF EVENTS BEGINNING OCTOBER 08, 2001

Early on the evening of October 07, 2001 08:23 PM EDST, local time (October 08, 2001, 00:23 UTC) felt earthquake reports began coming into various media outlets in the Augusta/Aiken area from surrounding towns of New Ellenton, Williston, Jackson, and south Aiken. SRS Emergency Operations also received a number of inquiries. Reports of a loud thump or large explosion were the most common descriptions of the event. With this occurrence being so close to the September 11, 2001 terrorist attack less than a month earlier, many initially thought that something similar might have happened at the

SRS. This was, however, not the case. A small earthquake had occurred. The event was well recorded on instruments within the SRS monitoring network and many stations of the South Carolina Seismic Network (SCSN) (Figure 1).

The SRS network is a nine–station short–period network located within and just outside the bounds of the SRS. The network was originally established in 1976 and continues operation today recording and documenting baseline seismic activity that may occur within the immediate SRS area. The SCSN currently consists of 22 stations scattered through major parts of South Carolina and has been in continuous operation since 1974.

Phase data obtained from 16 local and regional stations were input into the location algorithm (HYPOELLIPSE, Lahr, 2000). The final hypocentral location of 33.32° N, longitude 81.67°, depth 3.90 km and an origin time of 00:23:01.12 UTC was obtained using seven P phases and four S phases from local stations of the SRS seismic network. Epicentral distances of these stations were between 1.4 and 30 kilometers. Two eight layer P wave velocity models developed for the southern region of SRS and for the upper Coastal Plain were used. Shallow layers of the velocity model were developed from a velocity log in a 1 km deep well within SRS and deeper layers were derived from a seismic refraction profile through the Coastal Plain (Luetgert *et al.*. 1994). This location places the event in the north central area of the SRS (Figure 2).

Review of network data in the days and weeks preceding the earthquake showed no evidence of foreshock activity preceding the main October 08 event. However, seven aftershocks were recorded and located (Table 1). The first two followed the main shock by 2 hours 23 minutes and 8 hours 30 minutes respectively. Two more occurred on day six and day seven. The next two occurred two months later in December, 2001 and the latest occurred five months later in March, 2002. All aftershocks had duration magnitudes of between 0.1 and 1.4 with the March, 2002 event being the largest. All locations fell in the same general area as the main event with depths of between roughly 3 and 5 km. Four stations were located within 8 km of the center of activity ensuring small errors in hypocentral locations (Table 1) and allowing us to consider the computed locations for identification of seismogenic features. Before identifying the seismogenic features associated with the Upper Three Runs earthquake sequence we present a brief overview describing the tectonics of the region and its earthquake history.

TECTONIC SETTING AND HISTORICAL SEISMICITY

The SRS and the epicentral area lie approximately 30 km east of the Fall Line (Figure 3) within the upper Coastal Plain physiographic province which is characterized by seaward thickening, relatively flat lying, unconsolidated sedimentary sequences. The Coastal Plain sediments begin with zero thickness at the fall line, increase to a thickness of approximately 335 m near the center of SRS (epicentral area), and reach a maximum thickness of near 1.2 km at the Atlantic coast. West of the Fall Line lie several, extensively documented lithotectonic terranes that comprise the Appalachian orogen. These terranes generally occur in long narrow northeast-southwest trending belts separated from each other by faults of the Eastern Piedmont Fault System, inferred to be of late Paleozoic to early Mesozoic in age (Hatcher et al., 1977). The subsurface structure has been determined from extensive geophysical data and deep borehole cores that penetrate the Coastal Plain (Marine and Siple, 1974, Cumbest et al., 1992, Stieve and Stephenson, 1995). The hypocenters lie on the downdip continuation of the Kiokee and Belair belt rocks that outcrop northwest (Figure 3).

Since 1897 there have been 22 earthquakes located within 80 km of the Upper Three Runs earthquake sequence (Figure 2, Table 2). The earliest reported felt activity occurred in May of 1897 with three small events reported near the town of Blackville, South Carolina and one near Batesburg. No intensity values have been assigned to these events as they have only been mentioned as being felt (Visvanathan, 1980). When researching local newspapers of the area, the only reference found for the Blackville events appeared as a small sentence in the May 13, 1897 issue of the *Barnwell People* from Blackville, quoting, "Quite an earthquake shock was felt here on last Friday evening at 8:10." No mention of the two other 1897 events on May 24 and May 27 was found in newspapers published shortly following those dates.

There appears to be a hiatus in activity (or documentation), as the next recorded event occurred in 1972. Since 1972, there have been five events with $M \geq 3.0$ of which only three occurred in the Coastal Plain, all of them outside and within ~25km of SRS. Of these, the m_{blg} 3.2 August 08, 1993 Aiken, South Carolina event was studied in detail and found to lie within a steep gravity gradient associated with the edge of a granitic pluton (Stevenson and Talwani,1996). However, another well-studied small event (MD = 2.6 on June 09,1985) that occurred within the SRS was found to be associated with northwest trending feature observed in the detailed gravity of the epicentral area (Talwani, *et al..,* 1985). Much of the documented seismicity occurring outside the Middleton Place Summerville seismic zone near Charleston, South Carolina has been attributed to Reservoir Induced Seismicity. However, the historical activity presented above is evidence that low magnitude shallow earthquakes not associated with reservoir impoundment do occur within the upper Coastal Plain and Piedmont regions of South Carolina. We next examined the Upper Three Runs sequence in light of the tectonics and historical seismicity of the region.

SEISMOTECTONIC ASSOCIATIONS

In order to define the seismogenic source associated with the Upper Three Runs sequence we first determined its focal mechanism. Impulsive data from 16 stations of the South Carolina and SRS seismic networks and one SCEPP station allowed for the determination of a well constrained fault plane solution. The resulting focal solution shows predominantly normal, dip-slip motion either striking northwest at 350º and dipping 50º northeast or striking northwest at 335º dipping 41º southwest (Figure 4a). If the phase data for the aftershocks are added, there is little change to the resulting composite fault plane solution with the strikes shifting clockwise 10º with no change in the dip (Figure 4b). This suggests that the aftershocks are occurring on essentially the same fault plane as the main shock. The epicentral distance to the nearest station, for the main shock (1.4 km) and aftershocks (<0.5 km) allowed for extremely accurate hypocenter locations.

Additionally, impulsive S waves observed on the three-component digital data further improved the hypocenter locations. The close epicentral distances and the use of S – phase data ensure very accurate hypocentral locations (Gomberg et al., 1990).

In order to choose between the two nodal planes of the fault plane solution presented in Figure 4, we plotted the hypocenters in 3D. Using a software package designed for 3D geologic model building and visualization (EarthVision®, developed by Dynamic Graphics) we plotted the eight hypocenters (Figure 5). The plane defined by the hypocenters was found to strike NNW at 342° (Figure 5A line I J) and dip at 32° to the southwest (Figure 5A plane ABCD). This agrees very well with the southwest dipping plane in the focal mechanism solution (Figure 4). Consequently, the NNW striking, southwest dipping fault plane was interpreted to be the preferred fault orientation associated with the Upper Three Runs sequence of earthquakes.

The epicenters were also plotted on a detailed gravity map of the SRS (Anderson, 1990). The regional pattern of the gravity contours (0.5 mGal contour interval) is NE-SW (Figure 6A). The contours in the epicentral area are interrupted by a NW-SE trending feature, with epicenters lying on its NE flank. In order to delineate this NW-SE feature we obtained the horizontal gradient map of the area (Figure 6B). The horizontal gradient map clearly outlines a narrow NW-SE trending structure to the northeast of which lie the epicenters. The horizontal gradient map suggests that the seismicity is associated with a small northwest trending structure embedded within the NE-SW regional trend. We note that the northwest trend of epicenters flank the buried structure near its intersection with a regional northeast geologic trend with similar geometry to that observed for the M2.5, June 1985 event (Talwani et al., 1985). The inferred shallow NW-trending body lying adjacent to the regional NE trend is not apparent in the reduced-to-the-pole residual magnetic anomaly map (Figure 7).

CONCLUSIONS

In conclusion, the "Upper Three Runs" earthquake sequence occurred within a local microearthquake monitoring network. Due to the short hypocentral distances and availability of digital three component data these earthquakes were located with an accuracy of better than ±0.5km. The availability of a detailed gravity map with a contour interval of 0.5 mGal made it possible to isolate (and identify) shallow structures. This sequence of earthquakes was found to lie on a NNW-SSE shallow feature near its intersection with a regional NE trending feature supporting the idea of stress concentrations in the vicinity of intersecting faults (Talwani, 1988).

This data set has provided a remarkably clear picture of a fault plane defined by computed hypocenters corresponding closely with first motion focal solutions. The data also demonstrate that shallow intersections of structures interpreted from potential field data can be the foci for localized stress concentrations where microearthquake activity ($M \leq 3.0$) can occur. The shallowness and small aerial extent presented by this activity, and relationship to a very small basement feature running counter to the regional structural trend suggest that this activity is extremely localized. Additionally, the

“Upper Three Runs” example illustrates how a well recorded earthquake sequence using a microearthquake network and detailed potential field data can be used to study the genesis of small intraplate earthquakes.

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Figure 1. Short-period seismic stations of the SCSN and SRS seismic network and footprint of the SRS. Upper Three Runs series of events is nearest to station SRAV.

Figure 2. Historical earthquakes within 80 km (50 mi.) radius of most recent Upper Three Runs activity. Numbers correspond to event numbers in table 2. Event 23 is main event of this series..

Figure 3. Generalized geologic map of basement lithologies beneath the Savannah River Site and vicinity with adjacent piedmont (modified from Bramlett et al., 1982 and Dennis et al. 1996). Interpretations listed in key are derived mainly from outcrop observations. Individually labeled features within Coastal Plain (southeast of Augusta Fault) are interpreted from available drill core data and/or potential field data. Current earthquake sequence is represented by filled circle in north central portion of SRS.

Figure 4. Lower hemisphere equal – area fault plane solution for the October 08, 2001 Upper Three Runs event (A) and composite fault plane solution of the main event and six aftershocks (B) (Reasonberg and Openheimer, 1985). Strike dip and rake as noted.

Figure 5. (A) 3D view of fault plane (ABCD) as defined by hypocenters (filled black squares) looking northeast. The intersection of a horizontal plane (EFGH) with the fault plane defines the strike (IJ) of the fault plane as 342º dipping approximately 32º to the southwest. (B) View of Figure 5A looking north showing side view of fault plane (AD) from a point below the surface illustrating fit of hypocenters to fault plane. Errors in depth estimates are approximately ±0.5 km for all events except two (Table 1). Vertical scale is kilometers below surface.

Figure 6. Detailed gravity maps of epicentral area with Upper Three Runs earthquake sequence plotted as filled triangles (Anderson, 1990) (A) Bouguer anomaly map, (B) First horizontal derivative of gravity map (E. Wildermuth, 2003 personal communication).

Figure 7. A detailed view of aeromagnetic map of the epicentral area (Daniels et al.1983). Epicenters are represented by filled triangles.

Table 1: Upper Three Runs earthquake sequence

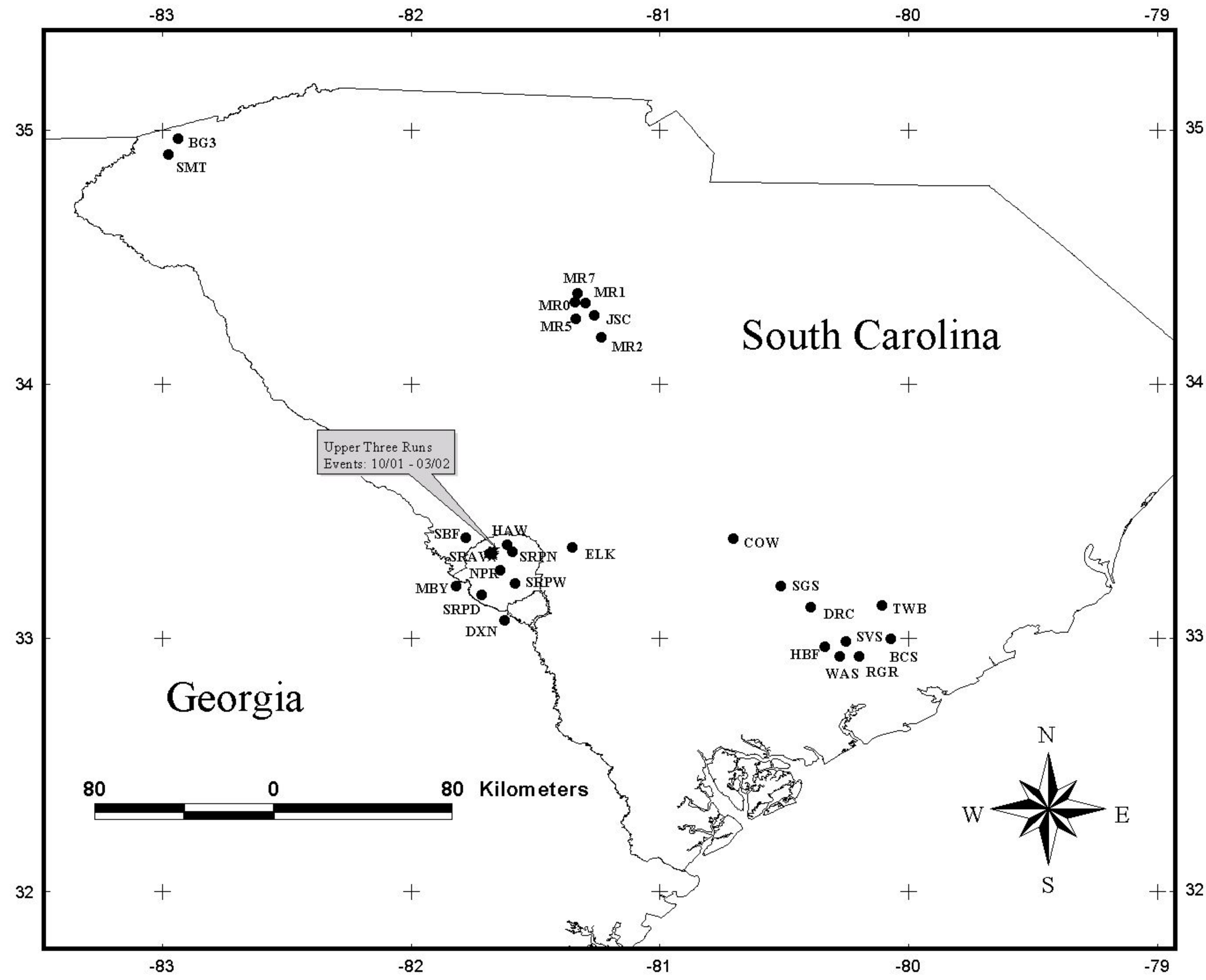
Event No. *	Date YMD	Origin time	Lat. (N)	Long. (W)	depth (km)	Mag.	No.	Gap	rms	seh	sez	Q
23	20011008	002301.12	33.3240	81.6650	3.9	2.6	10	136	0.04	0.5	0.8	b
24	20011008	025607.71	33.3193	81.6733	4.19	1.0	10	96	0.04	0.5	0.5	a
25	20011008	085351.08	33.3317	81.6762	4.15	1.4	11	202	0.06	0.5	0.5	b
26	20011014	060508.53	33.3467	81.6627	3.14	0.7	6	218	0.02	0.8	1.0	b
27	20011015	221806.60	33.3475	81.6938	4.67	0.8	13	225	0.08	0.9	0.5	b
28	20011217	334048.88	33.3283	81.6745	4.13	1.1	11	190	0.03	0.4	0.4	a
29	20011227	224504.59	33.3310	81.6652	3.76	0.1	10	172	0.06	0.4	0.5	a
30	20020306	000031.08	33.3313	81.6792	4.61	1.4	12	203	0.08	0.5	0.4	b

* Event numbers correspond to Figure 2 and Table 2

Table 2: Historic and Instrumental Earthquakes Recorded Within 80 km of Upper Three Runs sequence

Event #	Date	Latitude	Longitude	Depth (km)	Magnitude
1	05/06/1897	33.3	-81.2		Felt
2	05/09/1897	33.9	-81.6		Felt
3	05/24/1897	33.3	-81.2		Felt
4	05/27/1897	33.3	-81.2		Felt
5	8/14/1972	33.2	-81.4		3.2
6	10/28/1974	33.79	-81.92		3.0
7	11/5/1974	33.73	-82.22		3.7
8	9/15/1976	33.1440	-81.4130	4.50	2.4
9	6/5/977	33.0520	-81.4120	3.50	2.7
10	2/21/1981	33.5933	-81.1476	6.61	2.0
11	1/28/1982	32.9800	-81.3900	7.00	3.4
12	6/9/1985	33.2225	-81.6842	5.81	2.6
13	2/17/1988	33.5113	-81.6966	11.73	2.5
14	8/5/1988	33.1873	-81.6290	2.26	2.0
15	7/13/1992	33.4798	-81.1920	7.60	1.9
16	10/2/1992	33.4990	-81.2020	3.00	2.4
17	12/12/1992	33.2798	-81.8328	11.80	1.2
18	6/29/1993	33.4652	-81.2210	4.90	2.2
19	8/8/1993	33.5893	-81.5852	10.18	3.2
20	8/8/1993	33.5885	-81.5812	9.22	1.6
21	9/18/1996	33.6915	-82.1248	2.38	2.8
22	5/17/1997	33.2118	-81.6765	5.44	2.5
23	10/08/2001	33.3240	-81.6650	3.90	2.6
24	10/08/2001	33.3193	-81.6733	4.19	1.0
25	10/08/2001	33.3317	-81.6762	4.15	1.4
26	10/14/2001	33.3467	-81.6627	3.14	0.7
27	10/15/2001	33.3475	-81.6938	4.67	0.8
28	12/17/2001	33.3283	-81.6745	4.13	1.1
29	12/27/2001	33.3310	-81.6652	3.76	0.1
30	03/06/2002	33.3313	-81.6792	4.61	1.4

Source: SEUSSN Bulletins, Virginia Tech Publication; through 12/00. SRS unpublished data: 01/01 through 6/27/02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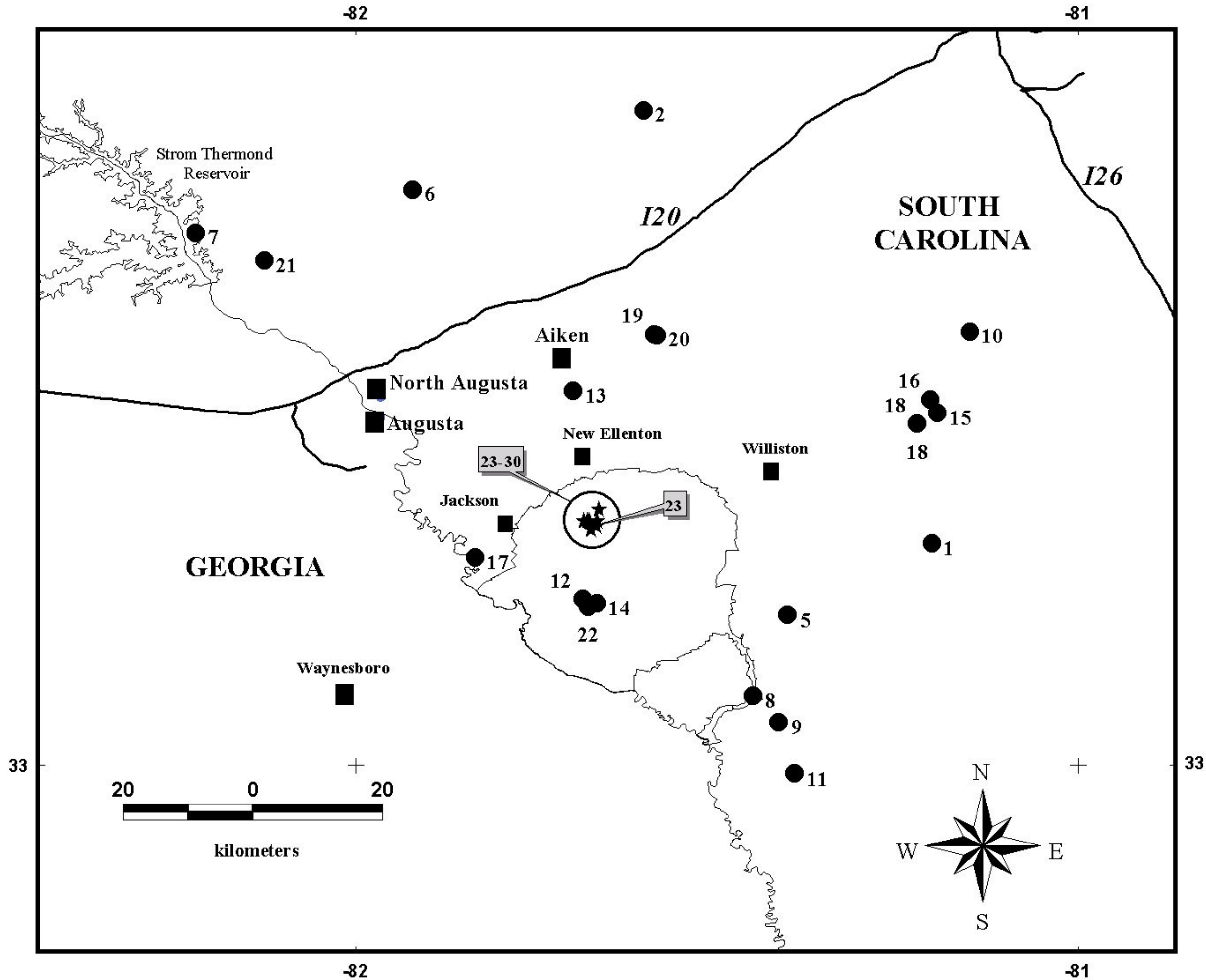

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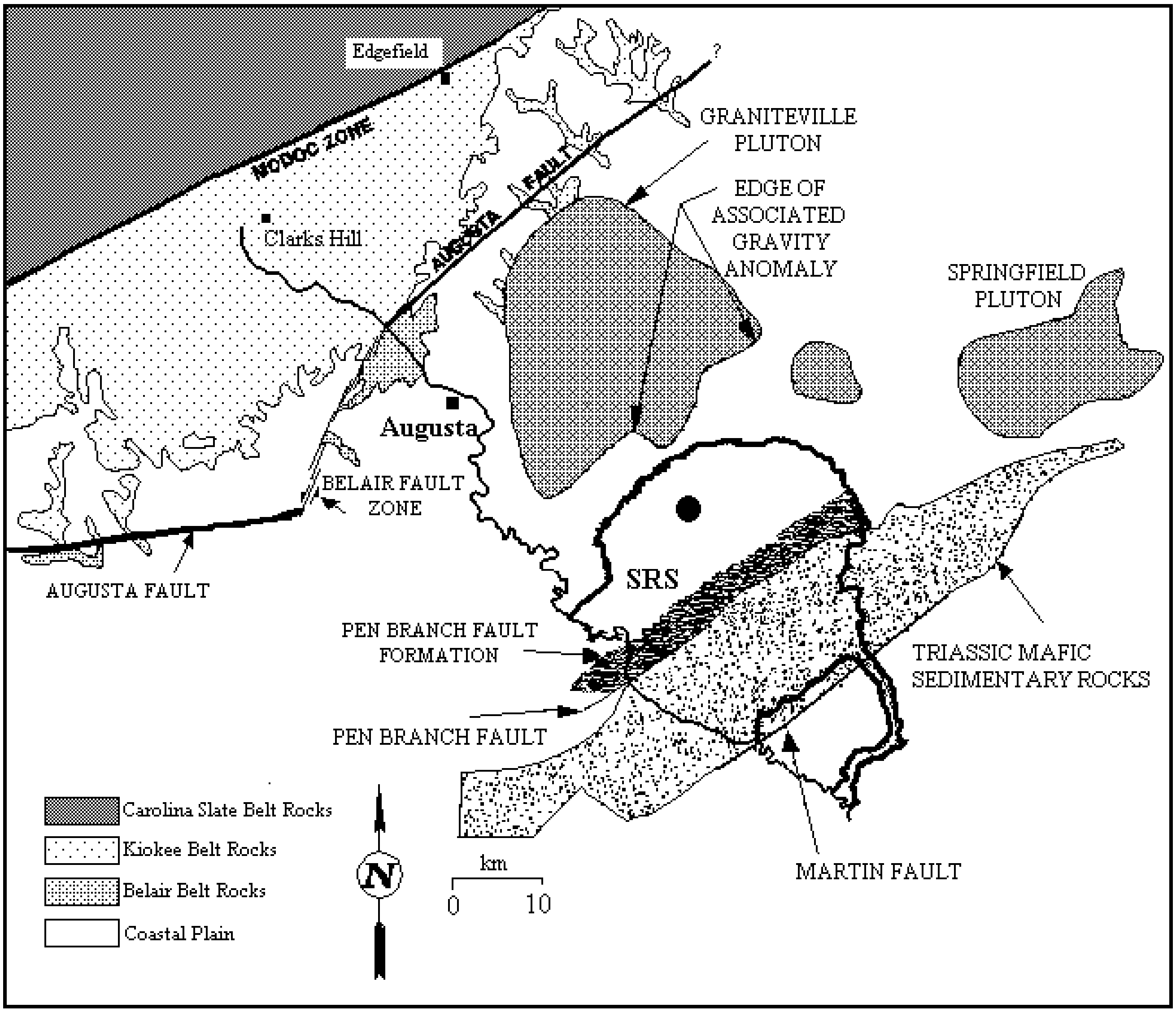
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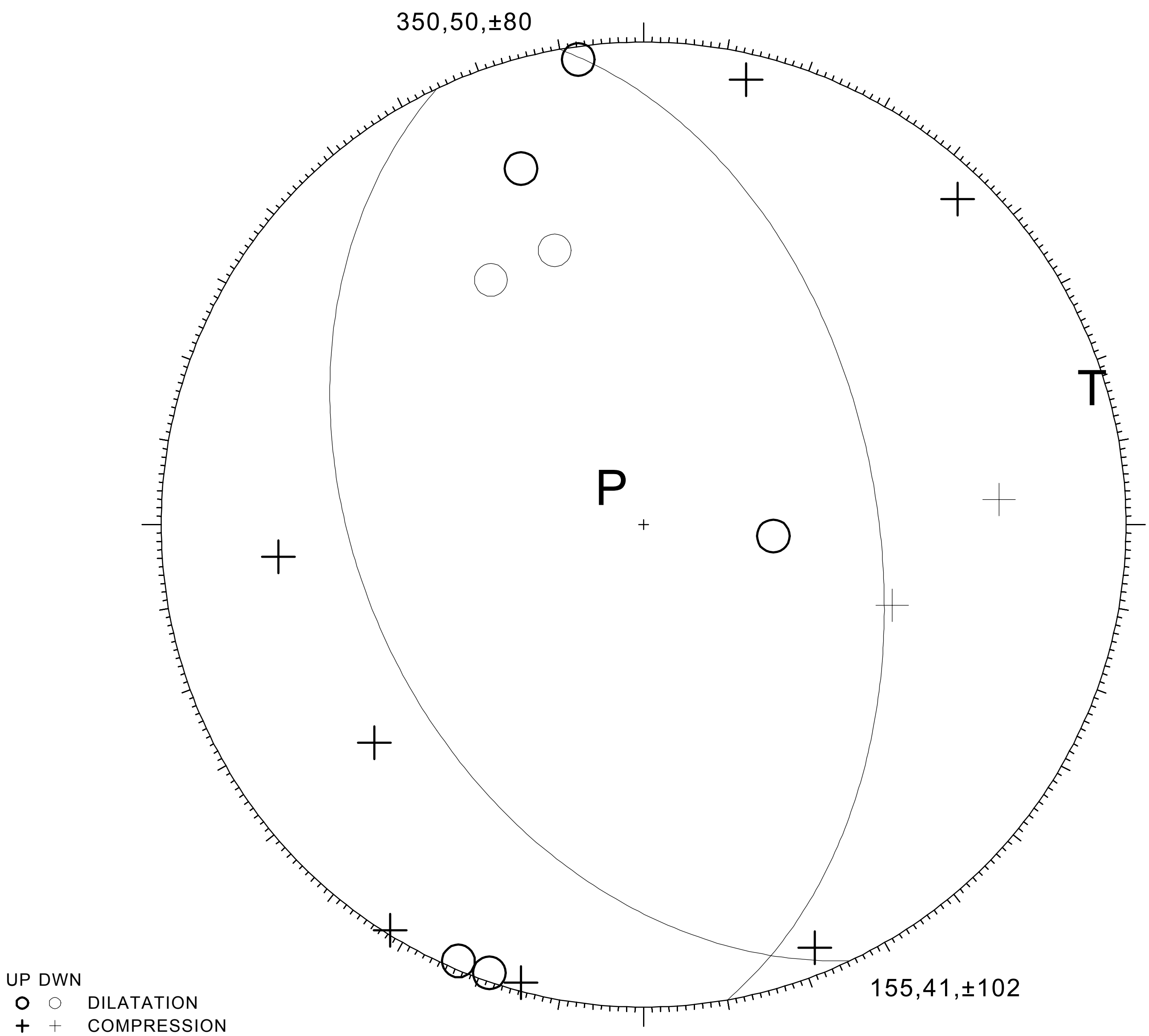
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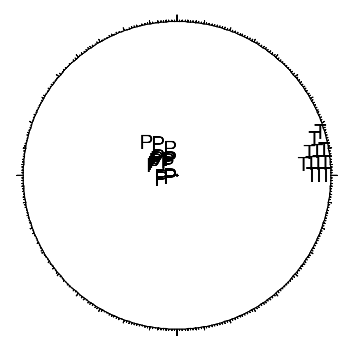

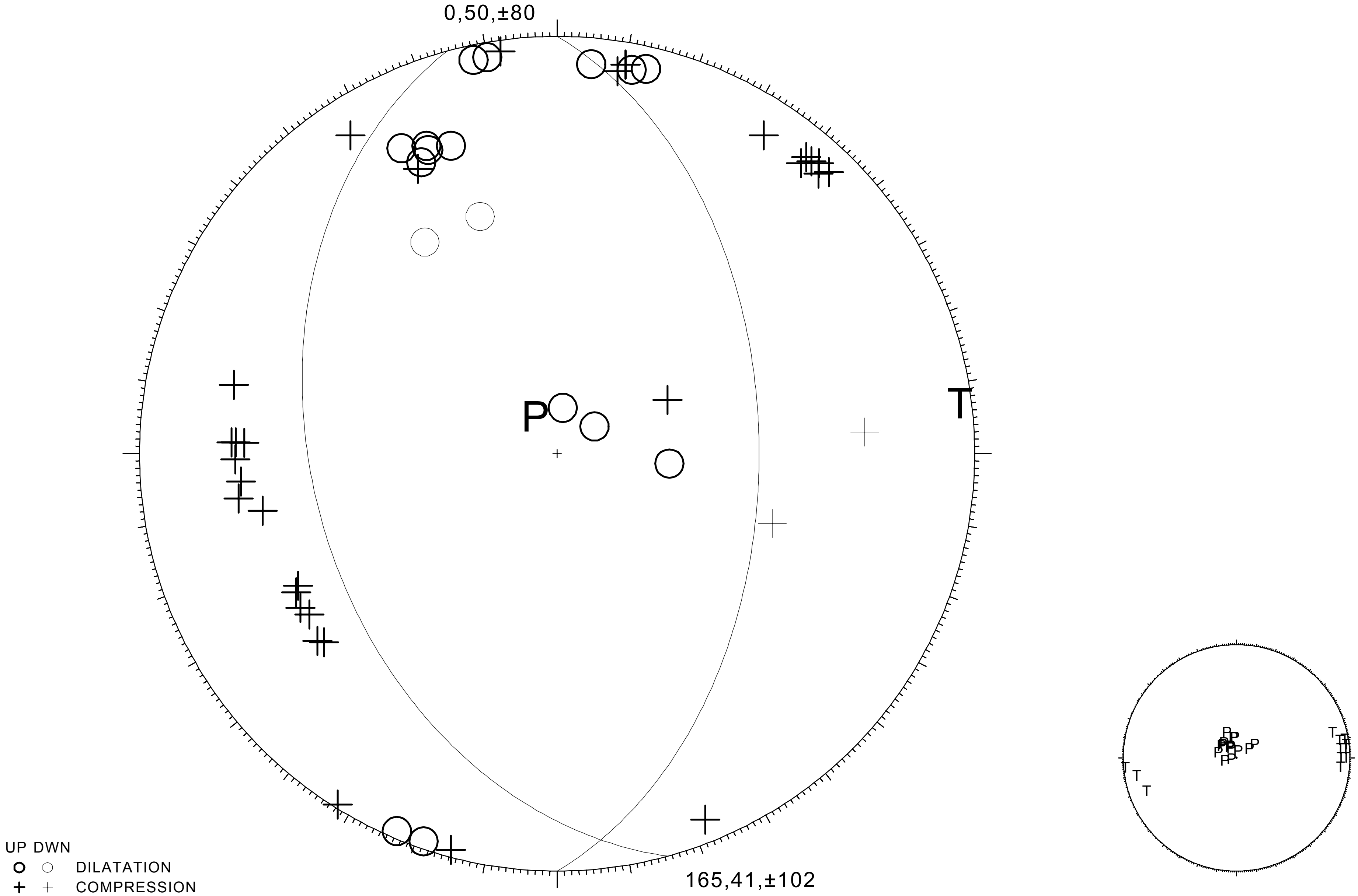
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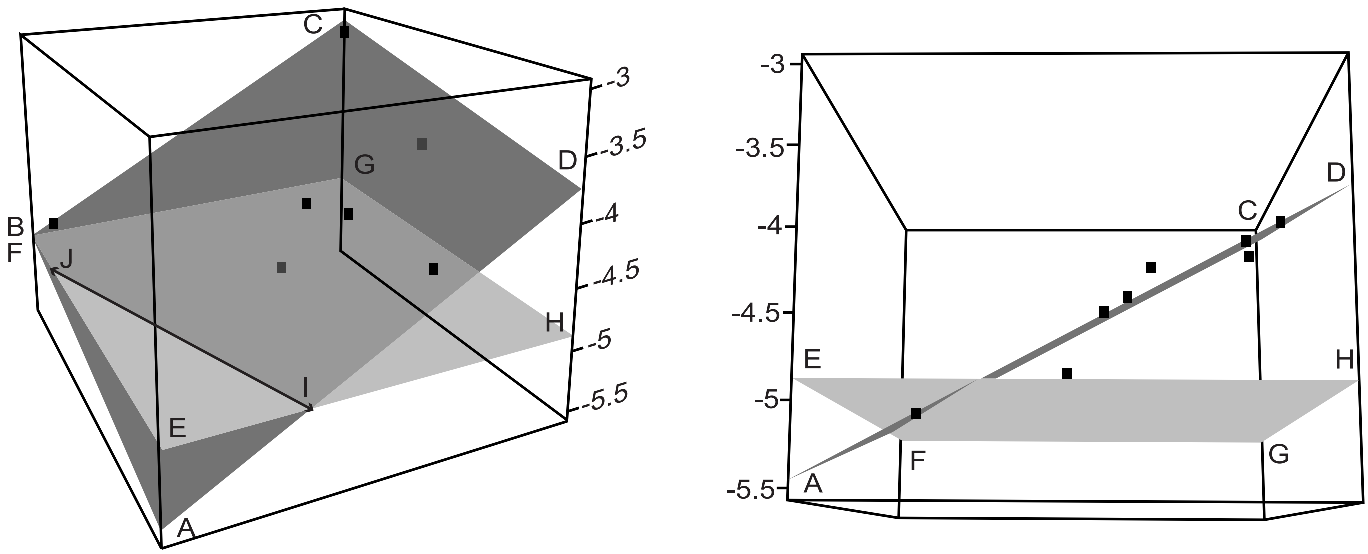

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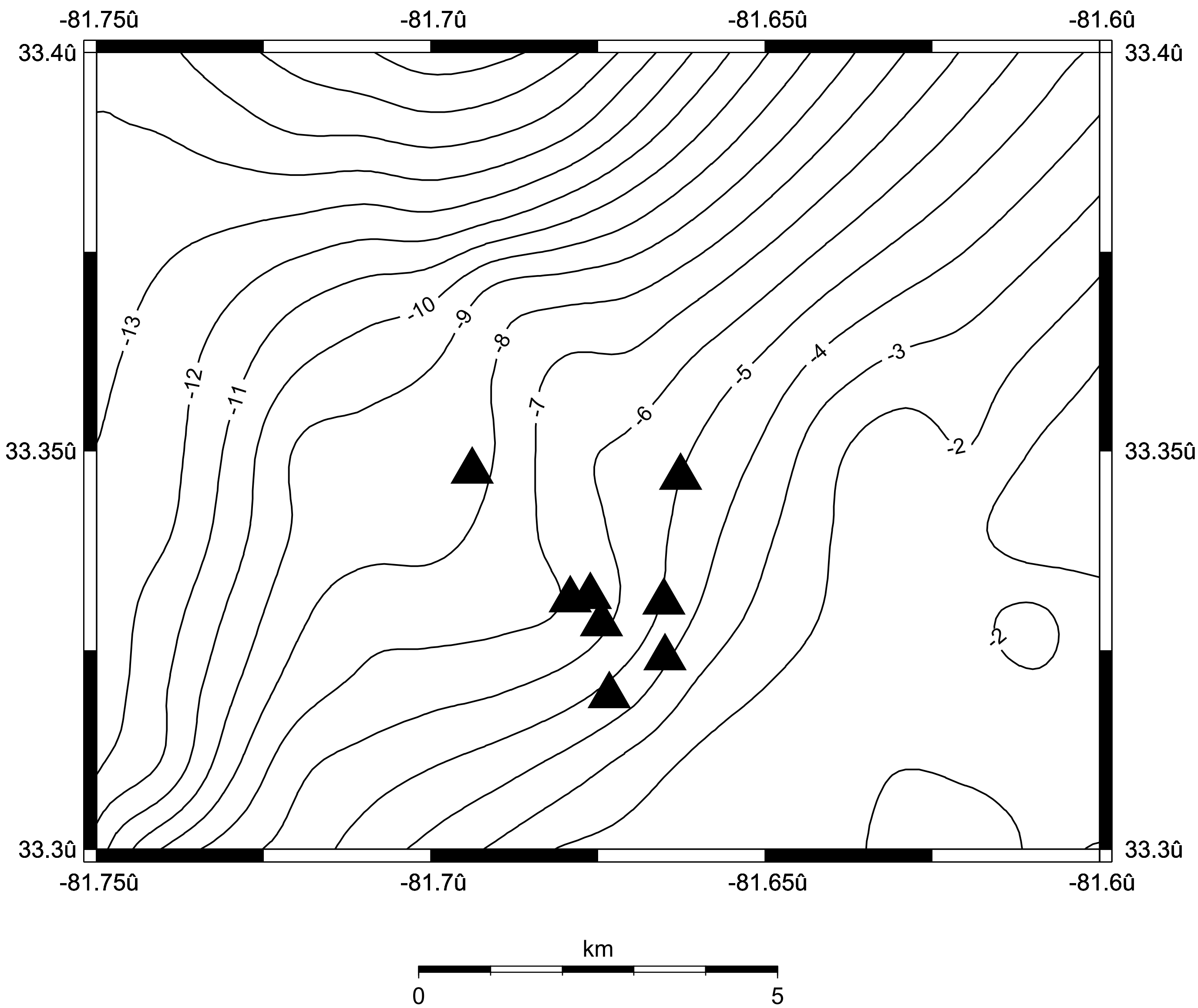
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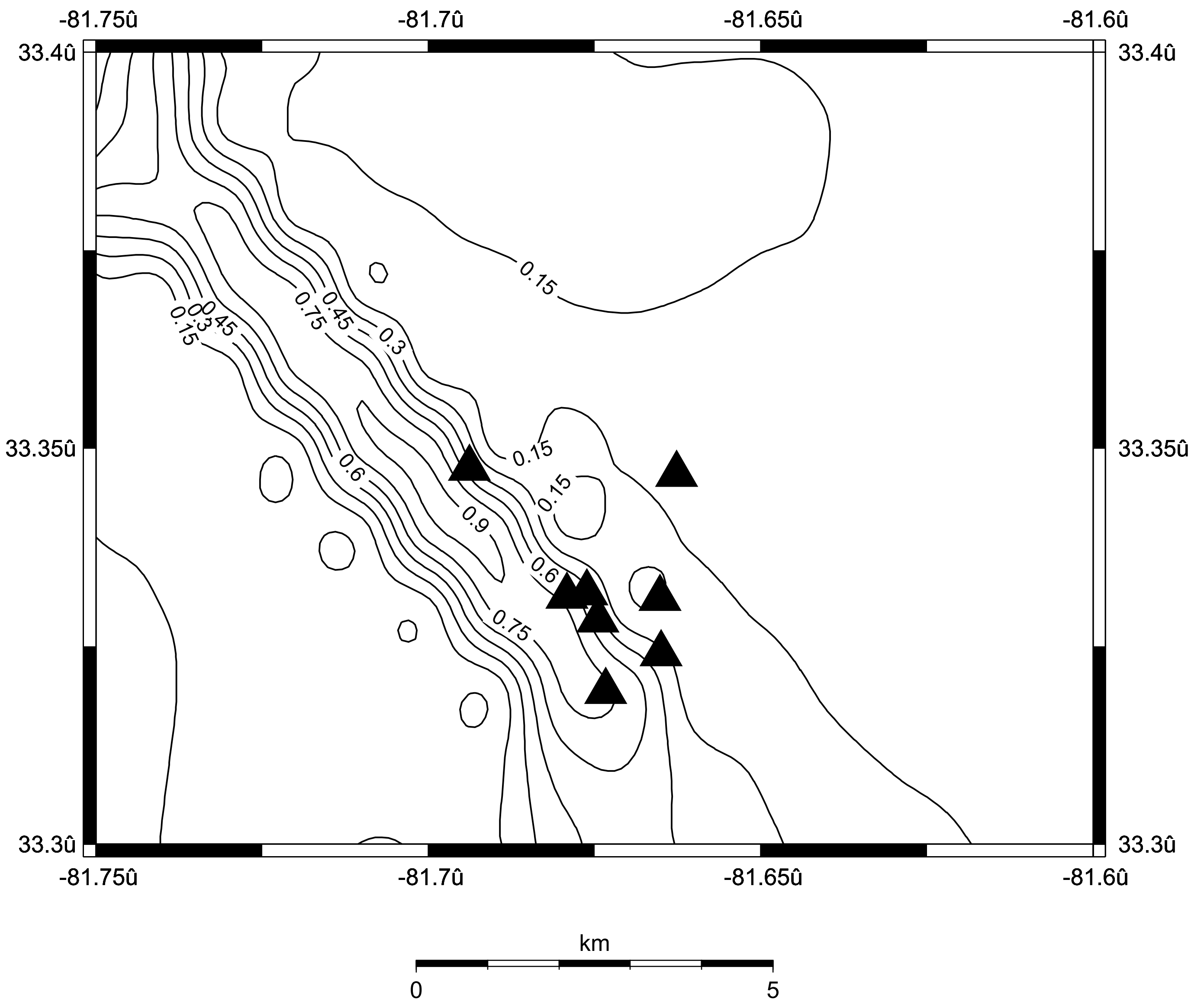
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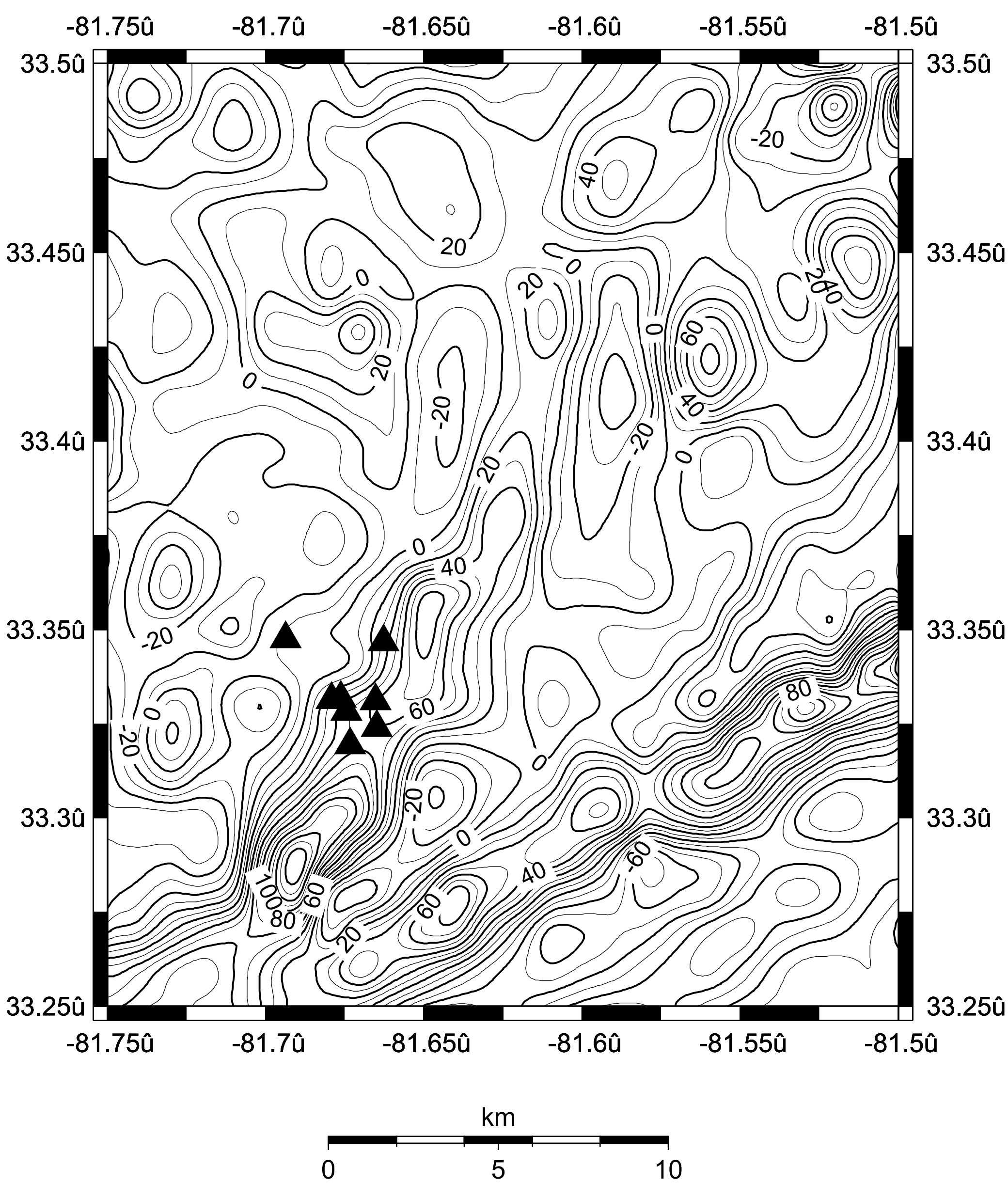
-81.75û
-81.7û
-81.65û
-81.6û
-81.55û
-81.5û
33.5û
33.45û
33.4û
33.35û
33.3û
33.25û
-20
40
20
0
60
-60
80
100
km
0
5
10