USGS/NEHRP Final Technical Report:

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SEISMOTECTONICS OF SOUTH AND WESTERN PUERTO RICO: MUERTOS TROUGH DOWNGOING SEISMIC ZONE AND OVERRIDING PLATE SEISMICITY

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Abstract

The objective of this project was to better define the location and tectonic character of the Muertos megathrust beneath southern Puerto Rico. Two principal means of data analysis were used to accomplish this objective, double-difference relocation of microearthquakes recorded be the local network, and single event and composite focal mechanisms of events on or near the presumed Muertos Megathrust. Both efforts were successful in better defining the location and nature of the megathrust.

The program *DD* was used on the catalog data for events located by the local seismic network (PRSN) for the period 1975-2001. Events were selected on geographic and quality criteria. Microearthquakes in the region bounded by latitude 17.4º to 18.8º N and 65.4º to 67.5º W in all depth ranges were selected and of those, events with at least 4 P wave arrivals, a total of 5,880 events, were passed to *DD* for relocation. P- and S-wave arrivals were considered in the relocation process, but S arrivals were given half the weight of P arrivals. Events were relocated using the 1-D velocity model developed in a previous NEHRP project using the program *Velest.* In all, *DD* determined 22 clusters of events, the first cluster had 1533 events, and the rest totaled only 100 events.

With this improved location of some 1500 earthquakes the general geometry of the region was examined through maps and vertical cross sections. They show the same general distribution as with the catalog of events developed using *Velest*, however, with much less scatter. In some vertical cross sections the downgoing seismic zone (W-B) is clear, and in others there is a W-B seismic zone, and significant activity in the crust above the downgoing plate as well.

Of these well-located microearthquakes, events were chosen to construct single and composite fault plane solutions. Events with 4 or more first motions were selected and grouped so that no event in any given composite solution was more than 5km in latitude or depth and 13 km in longitude from other events. First motions at a given station were then compared so as to select events with like similar focal mechanisms. *FOCPLT* was used to determine nodal planes and other focal parameters. Total number

of first motions for a mechanism range from 10 to 136, using between 1 and up to 15 events. A total of 83 events were used to develop 21 mechanisms, 20 of them composites.

Most striking from a simple examination of the focal mechanism results is the high number of normal fault solutions and virtual absence of low angle thrusting events, regardless of obliquity. GPS measurements, deformation along the inner wall of Muertos Trough, and the inclined seismic zone, would lead one to expect thrusting on shallowly northerly dipping planes, possibly with a high degree of oblique slip. Ten mechanisms represent reverse faulting, eleven normal faulting, and one strike-slip.

Introduction

The US territories in the Caribbean (Puerto Rico and the U.S. Virgin Islands) lie within an actively deforming plate boundary zone. The proper determination of earthquake hazard for these islands will be based on the identification and characterization of active faults and the determination of the seismicity associated with them. Unlike California, most of the active faults lie beneath the sea surrounding the islands or at depth in the subduction zones to the north and south of them. The subduction zone to the north, whose trace is the Puerto Rico Trench, has been recognized for more than 40 years. In contrast, the southern subduction zone, whose trace is the Los Muertos Trough, up until now has been a poorly defined, even debatable tectonic structure.

The Muertos Trough has been the site of convergence between the buoyant Caribbean Plate to the south and the microplates in the 200 km wide NOAM-CARIB plate boundary zone since at least Miocene time (Pindell et al., 2005). The best evidence for the convergence lies to the west of Puerto Rico in the mountainous parts of the western Dominican Republic on Hispaniola. There, accretionary prism material has been folded, faulted and thrust upward in response to the entrance of the bathymetrically high Beata Ridge into the Los Muertos Trough (Biju Duval, 1982). Ladd and Watkins (1978) and Ladd et al (1977), acquired seismic reflection data over the large forearc ridge/basin sequence that lay south and just east of the Dominican Republic. Byrne et al., (1985) report on strong earthquake (1984, Ms 6.7) reflecting northward directed underthrusting beneath the eastern part of the Dominican Republic. So, the evidence for modern convergence there is abundant.

Near Puerto Rico, we have every reason to believe that the neotectonic environment is similar to that of the Dominican Republic to the west. However, it is very different today than what is was in the recent past, and one could easily be confused by older tectonic events not operative today.

So is the Muertos Trough active today? Scanlon et al., (1987) identified an active deformation front where buoyant CARIB lithosphere first encounters and deforms material on the overriding microplate south of Puerto Rico (Figure 2). Silver et al., (1972) shows a seismic reflection line just off the west coast of Puerto Rico that crosses the Muertos Trough. In that profile the deformation front noted by Scanlon is clear, as are other structures typical of an active convergent margin. Regional models suggest that south of Puerto Rico it indeed still experiences some motion. While rates of motion for the Muertos Trough and Anegada Passage are not well constrained, GPS measurements suggest 3 mm/yr on each of these features (Jansma and Matiolli, 2005).

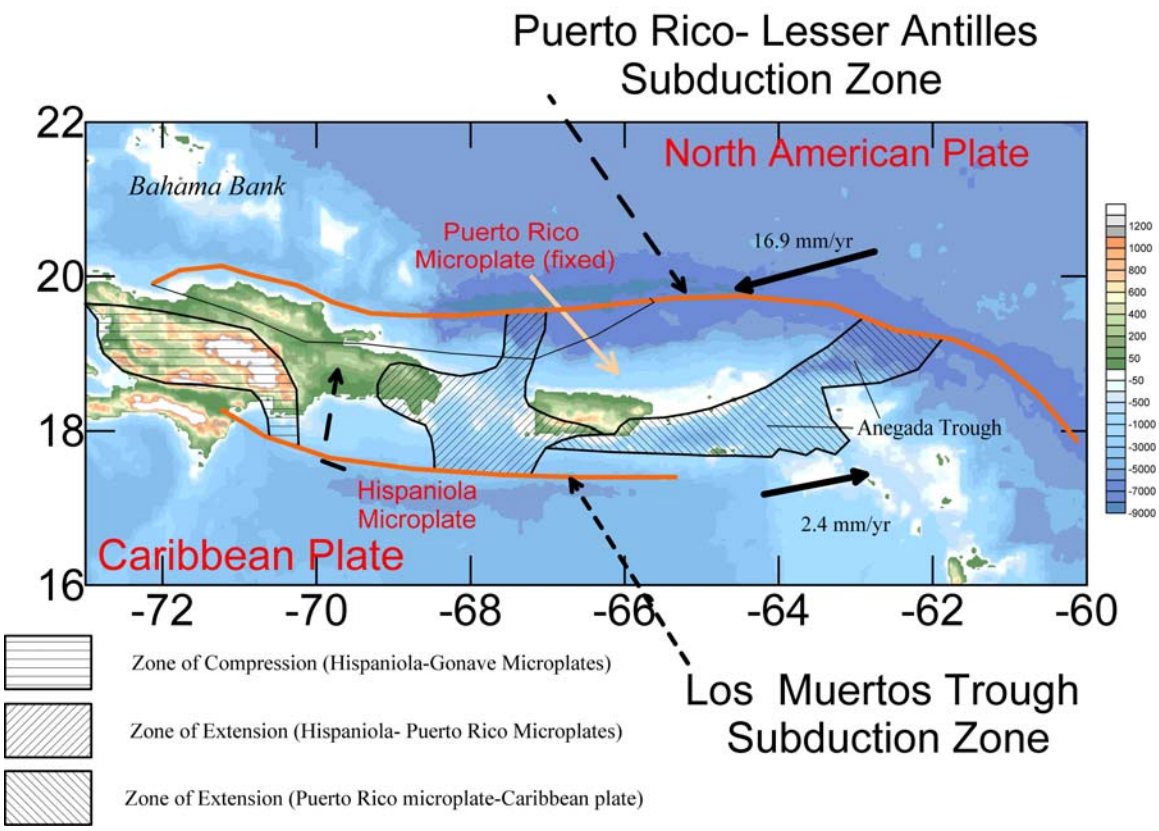


Figure 1. Tectonic setting of Puerto Rico and US Virgin Islands. The Puerto Rico Trench lies along the northern margin of the Puerto Rico microplate. The Muertos Trough lies along the southern margin to about 65°W. More to the East, the Anegada Trough is the principal locus of deformation. The wide zone of extension along the Western margin of the Puerto Rico microplate encompasses the Mona Passage and SW Puerto Rico. While the Puerto Rico Trench is the focus of most interplate motion, the nearby microplate boundaries and active faults associated with them represent an important earthquake threat. Arrows with numbers are GPS rates of motion with respect to PRVI in mm/yr (Jansma et al., 2000). This project investigated the southern margin of the Puerto Rico microplate, where it meets the Caribbean Plate.

Besides the Muertos megathrust there are several crustal structures that are believed to be responsible for the shallow microearthquake activity in southern and southwestern Puerto Rico. In fact most researchers suggest that crustal faults are primarily responsible for the high level of seismic activity in southwestern Puerto Rico. Specific tectonic structures that can be to investigated through microearthquakes are:

- Muertos Trough and Related Structures: An extensive, very shallow-dipping megathrust that appears to lay some 15 -20 km beneath much of S. central and S. western Puerto Rico.

- Western Region: Cerro Goden Fault- slip rate estimated ~0.5mm/yr; S. Lajas Fault- trenching shows 2 events in 7,000 yrs
- South Coast region: Baja Tasmanian and Caja de Muertos Faults- bound Ponce graben with up to 1100 m throw; Rio Jueyes and Salinas- Extend offshore with scarps of up to 15 meters, rates estimated at 0.14-0.19 mm/yr; Investigator Fault- 600m throw, capable of events larger than magnitude 7.
- Eastern Region: Cayey-Caguas Graben, extensional and strike slip mechanisms on features with 100's of meters of relief.
- The maximum depth of true "crustal" events will identify the brittle-ductile transition of the island. At the present time events are seen as deep as 30 km (i.e. throughout the entire crust). Fault length-magnitude relations for the island may have to be adjusted if in fact the whole crust is seismogenic.

Finally, properly located events can more reliably be used to develop a much-needed set of mechanisms of both crustal events and of those of the Muertos Megathrust.

A recently completed NEHRP project has developed new P- and S-wave velocity models for Puerto Rico and a new JHD catalog of over 15,000 well-located microearthquakes. A preliminary examination of that new catalog removes any significant doubts as to the existence of the Muertos megathrust beneath Puerto Rico. That megathrust lies only 15 km beneath the south coast of Puerto Rico, and although motion along it is relatively slow and oblique, about 3 mm/yr, it appears capable of producing interplate earthquakes as large as magnitude 8.0. Also, crustal seismicity not on the plate interface appears intimately related to the existence of the megathrust, with most shallow events are restricted to a region some 10 km or less above the megathrust. Investigation of these events will contribute to our understanding of the megathrust, and improve our knowledge of the seismic hazard of southern and western Puerto Rico. This project makes use of this abundant, local microearthquake data to determine the geometry and character of the Los Muertos Subduction zone and seismic activity in the overriding plate for later use in seismic hazard mapping. Events from 1975-2001 were located using the program *DD* to reduce relative location errors.

Relocation of microearthquakes using local network catalog data

The program *DD* was used on the catalog data for events located by the local seismic network (PRSN) for the period 1975-2001. Events were selected on geographic and quality criteria. Microearthquakes in the region bounded by latitude 17.4º to 18.8º N and 65.4º to 67.5º W in all depth ranges were selected and of those, events with at least 4 P-wave arrivals, a total of 5,880 events, were passed to *DD* for relocation. P- and S-wave arrivals were considered in the relocation process, but S arrivals were given half the weight of P arrivals. Events were relocated using the 1-D *Velest* velocity model developed in a previous NEHRP project. In all, *DD* determined 22 clusters of events, the first cluster had 1533 events, and the rest totaled only 100 events.

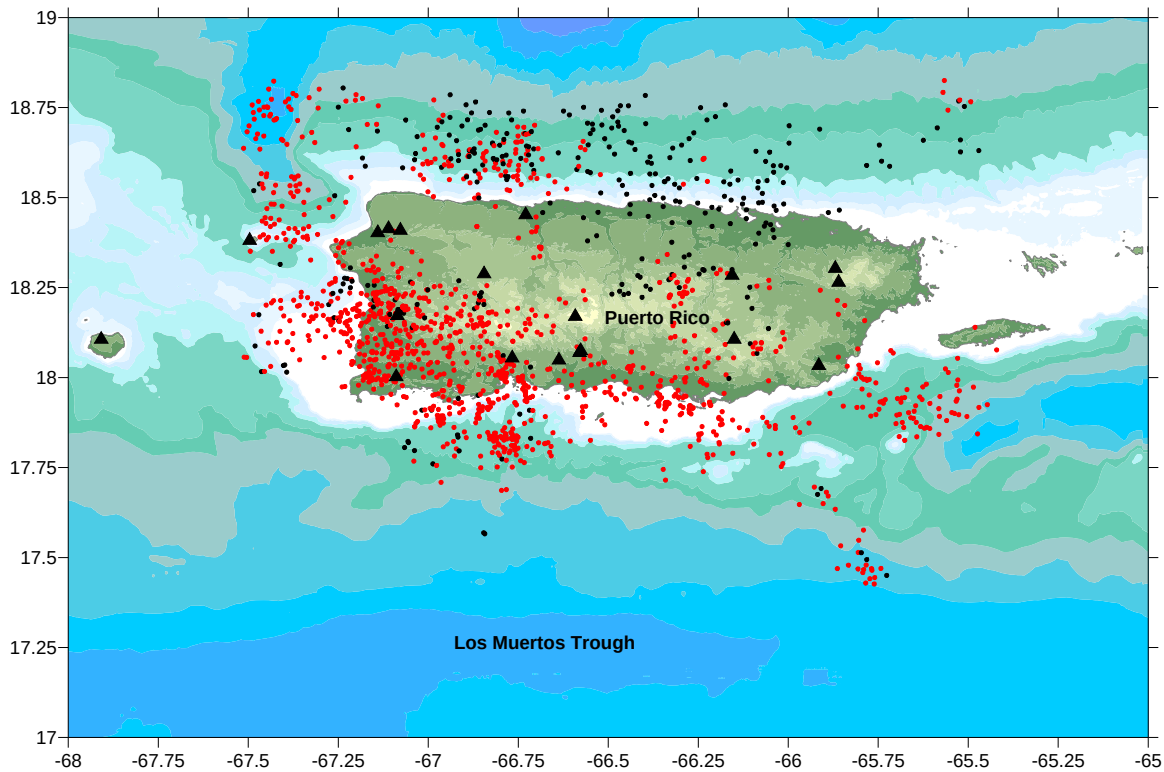


Figure 2. Cluster 1 *DD* event locations. Red circles are events 0-30km depth, black circles, deeper. Solid triangles are stations used to relocated events and form focal mechanisms.

With this improved location of some 1500 earthquakes the general geometry of the region was examined through maps and vertical cross sections. They show the same general distribution as with the catalog of events developed using *Velest*, however, with considerably less scatter. In some vertical cross sections the downgoing seismic zone (W-B) is clear, and in others there is a W-B seismic zone, and significant activity in the crust above the downgoing plate as well.

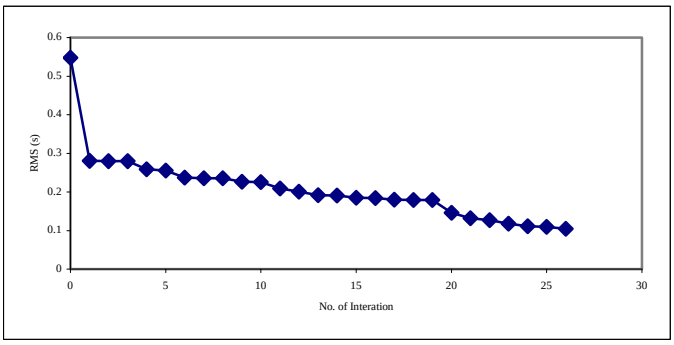
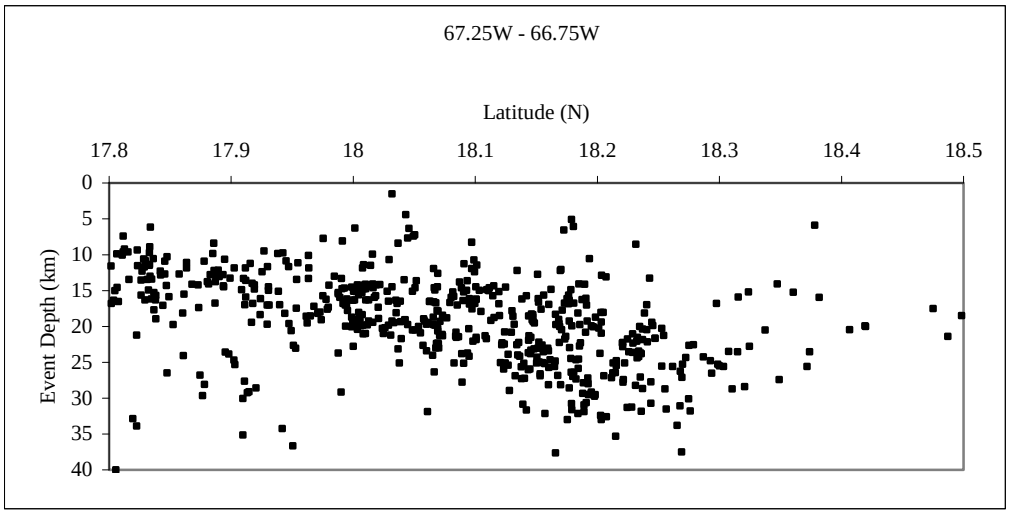
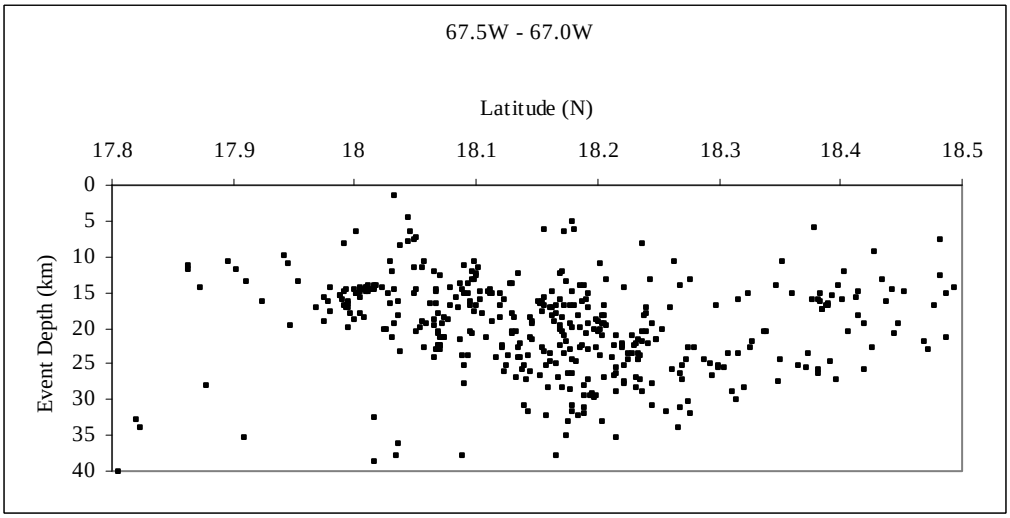


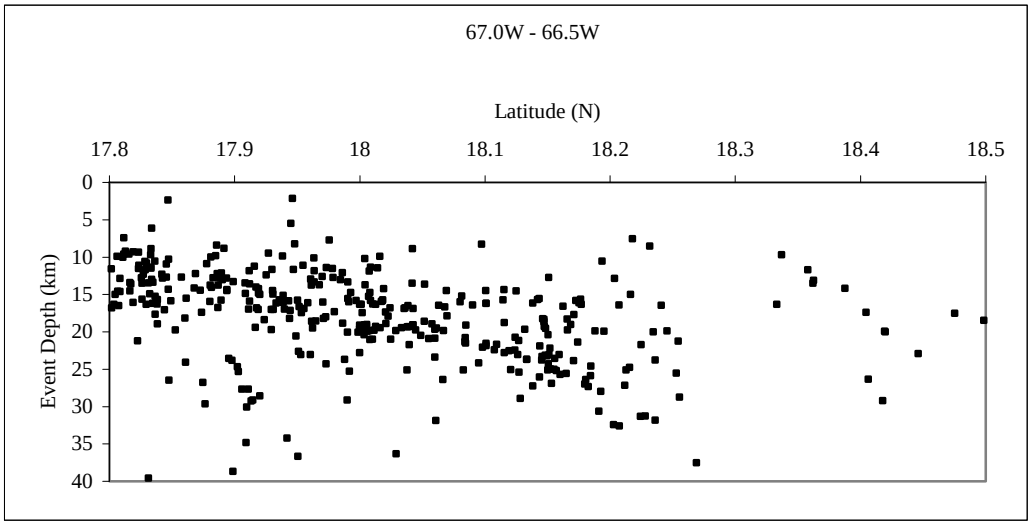
Figure 3. Change in RMS with successive iterations for Cluster 1 in the program *DD*. Note that besides the initial drop in RMS, there is a further 50% decrease in RMS.

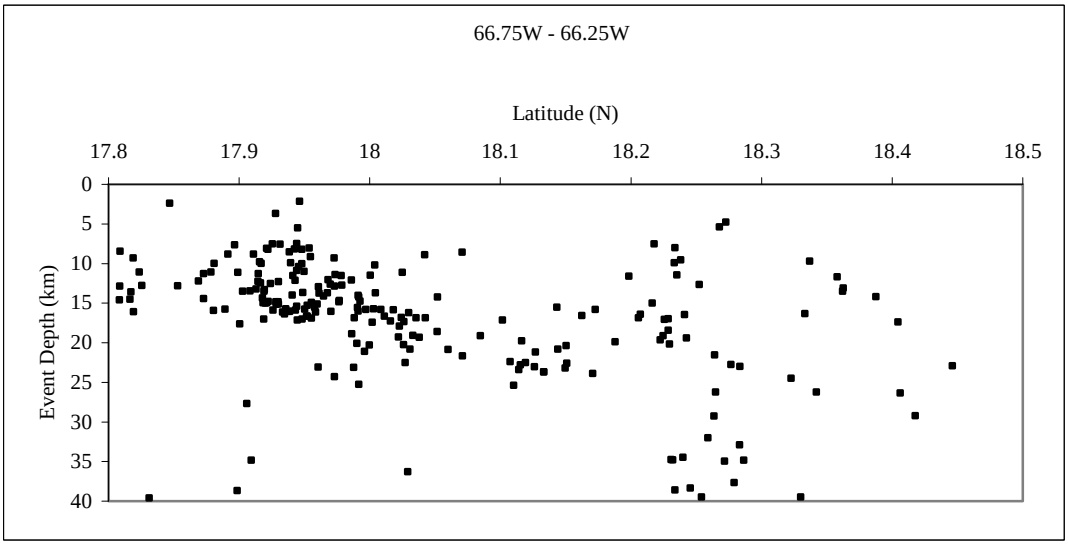
Below are 5 overlapping vertical cross sections of 50 km width each. Sections overlap adjoining ones by 25 km and are shown from west to east with the viewing direction from the east. The southern limit of the island of Puerto Rico, and thus the land stations, is about 18ºN and the northern limit is about 18.5ºN. A sedimentary deformation front associated with the descent of the Caribbean Plate beneath Puerto Rico is about 17.3ºN some 50 km to the left of a section edge.

The first section, 67.5-67.0ºW, is just along the westernmost portion of the seismic network and so location quality would rely highly on stations reporting, especially the two on the western islands of Mona and Desecheo. Seismicity defines a northerly dipping seismic zone, although relatively thick. Sections to the east, especially section 67.0-66.5ºW shows a thinner better-defined downgoing seismic zone. There is considerable seismic activity in the crust above the megathrust. The “kink” in the downgoing seismic zone at about 17km depth may be an artifact of the *Velest* velocity model used, as there is a velocity layer boundary at that depth.






67.0W - 66.5W
Latitude (N)
17.8
17.9
18
18.1
18.2
18.3
18.4
18.5
Event Depth (km)
0
5
10
15
20
25
30
35
40


66.75W - 66.25W
Latitude (N)
17.8
17.9
18
18.1
18.2
18.3
18.4
18.5
Event Depth (km)
0
5
10
15
20
25
30
35
40

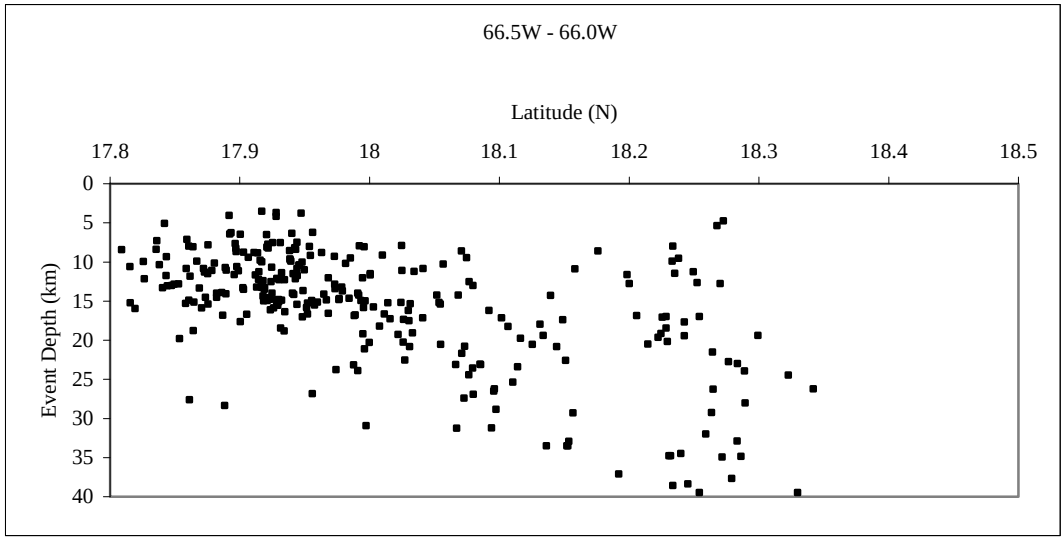


Figure 4. Five overlapping vertical cross sections showing the Muertos megathrust beneath southern Puerto Rico. Each section is 50 km wide and overlaps adjoining sections by 25km. The best section for visualizing the nature of the megathrust is 67º-66.5ºW.

Development of Composite and Single Focal Mechanisms

Next, events were chosen to construct single and composite fault plane solutions. Events with 4 or more first motions were selected and grouped so that no event in any given composite solution was more than 5km in latitude or depth and 13 km in longitude from other events. First motions at a given station were then compared so as to select events with likely similar focal mechanisms. *FOCPLT* was used to determine nodal planes and other focal parameters. Total number of first motions for a mechanism range from 10 to 136, using from 1 to up to 15 events. A total of 83 events were used to develop 21 mechanisms, 20 of them composites.

Most striking from a simple examination of the focal mechanism results is the high number of normal fault solutions and virtual absence of low angle thrusting events, regardless of obliquity. GPS measurements, deformation along the inner wall of Muertos Trough, and the inclined seismic zone, would lead one to expect thrusting on shallowly northerly dipping planes, possibly with a high degree of oblique slip. Ten mechanisms represent reverse faulting, eleven normal faulting, and one strike-slip.

Table 1. Focal Mechanisms derived using local network first motions.

						Prin			Aux			A			N			B			P			T							
Mch	#	NFM	NI	Wt	N	D	S	R	D	S	R	T	P	T	P	P	P	T	P	T	P	MRR	MTT	MPP	MRT	MRP	MTP
A	2	16	3	0.69	1	55	251	45	55	131	135	41	35	161	35	281	35	191	0	101	55	1	-0.95	0.28	-0.09	-0.46	0.24
B	3	32	2	0.74	2	33	67	69	60	271	103	181	30	337	57	85	11	352	14	212	72	0.85	-0.86	0.01	-0.47	0.12	-0.17
C	3	22	3	0.39	1	53	127	-65	44	269	-120	179	46	37	37	291	20	97	69	199	5	-0.87	0.88	-0.01	-0.04	0.35	-0.33
D	4	30	6	0.66	2	52	266	-80	39	70	-103	340	51	176	38	80	8	218	79	349	7	-0.95	0.93	0.02	0.26	-0.09	0.20
E	3	20	3	0.46	1	66	237	65	34	107	134	17	56	147	24	248	23	346	17	109	61	0.67	-0.83	0.16	-0.42	-0.48	-0.14
F	2	20	5	1.06	1	36	130	-55	61	269	-113	179	29	40	54	280	20	136	66	15	13	-0.78	0.80	-0.02	0.48	0.20	-0.32
G	2	20	2	0.28	1	74	291	86	16	125	104	35	74	201	16	292	4	24	29	195	61	0.53	-0.42	-0.11	-0.8	0.28	0.23
H	3	21	5	0.77	1	17	63	69	74	265	96	175	16	333	73	83	6	350	29	184	60	0.52	-0.50	-0.02	-0.84	-0.04	-0.15
I	8	46	11	1.91	1	76	261	53	39	154	158	64	51	171	14	271	36	18	22	133	46	0.37	-0.54	0.18	-0.67	-0.26	0.5
J	3	19	4	0.72	1	60	99	-57	44	227	-133	137	46	9	30	260	28	60	60	166	9	-0.73	0.85	-0.12	-0.36	0.33	0.34
K	3	25	7	1.43	1	47	110	-85	43	282	-96	192	47	20	43	286	4	79	86	196	2	-0.99	0.93	0.07	-0.05	0.09	-0.26
L	2	10	3	0.34	3	67	319	-66	33	91	-134	1	57	229	23	129	22	265	61	32	18	-0.66	0.65	0.01	0.29	-0.58	-0.38
M	5	37	12	1.84	12	24	82	80	66	273	94	183	24	352	66	91	4	360	21	192	69	0.74	-0.74	0.01	-0.67	0.07	-0.03
N	15	136	32	4.60	2	69	82	-83	22	242	-109	152	68	352	21	259	7	4	65	166	24	-0.66	0.61	0.05	-0.74	-0.06	0.21
O	7	47	6	0.85	1	43	49	78	49	245	101	155	42	319	47	58	8	327	3	217	81	0.98	-0.69	-0.28	-0.16	0.06	-0.46
P	4	22	4	0.74	2	39	102	-30	72	217	-125	126	18	12	51	229	33	87	51	332	19	-0.49	0.69	-0.2	0.25	0.64	0.39
Q	2	12	1	0.04	1	37	51	57	60	270	112	180	30	321	53	78	19	344	12	223	67	0.8	-0.8	0	-0.46	0.19	-0.33
R	2	17	2	0.55	2	75	284	71	24	157	140	67	66	194	15	289	18	29	27	170	56	0.48	-0.3	-0.18	-0.81	0.12	0.39
S	2	19	2	0.50	1	23	262	-90	67	82	-90	352	23	172	67	82	0	352	68	172	22	-0.72	0.71	0.01	-0.69	-0.1	0.1
T	2	10	2	0.24	1	86	8	12	78	277	176	187	12	278	4.2	27	77	142	6	233	12	0.03	-0.27	0.24	-0.04	0.22	-0.94
U	2	17	1	0.14	1	38	156	-55	59	294	-115	204	31	66	52	308	21	158	66	42	11	-0.8	0.39	0.41	0.49	0.01	-0.54
V	1	11	1	0.10	2	63	219	-79	29	15	-111	285	61	129	27	34	10	152	69	300	18	-0.78	0.14	0.65	0.43	0.41	0.34

Table Note- First Row: Prin Aux, Principal and Auxiliary Planes; A, N, B, P,T are A,N, B, P, and T axes as defined in *Focmech.* Second Row: Mch, letter identifying mechanism; #, NFM number of events and First motions used in mechanism; NI, Wt, N; number of incorrect first motions, and final solution weight, and number of solutions with that weight. D, S, R; Dip, Strike and Rake of plane. T, P; Trend and Plunge of axis. MRR, MTT, etc components of moment tensor.

Table 2. Events used to construct focal mechanisms

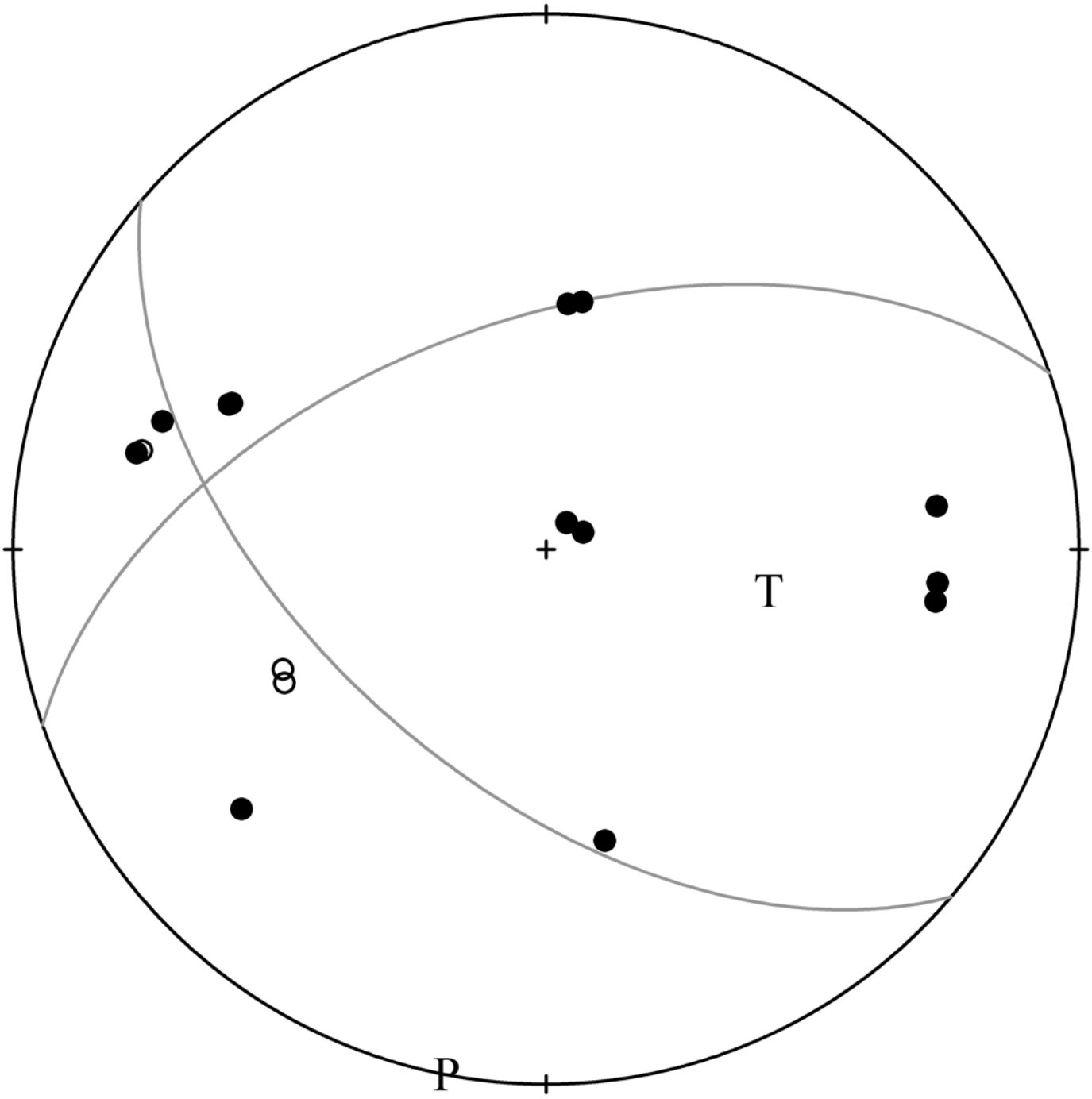
Mech	Year	Month	Day	Hour	Minute	Second	Longitude	Latitude	Depth	Magnitude
a	1993	10	6	18	18	30.4	-67.0615	18.1886	27.8	2.8
a	1996	3	22	6	45	47.9	-67.0716	18.1951	29.2	2.4
b	1998	5	22	3	9	35.0	-66.8331	18.1806	26.4	2.5
b	1996	7	14	23	40	14.3	-66.8232	18.1825	27.3	2.7
b	1997	9	6	20	26	44.2	-66.8312	18.1798	27.0	2.7
c	1993	1	21	7	48	56.7	-67.0635	18.2326	24.4	2.3
c	1998	4	26	10	27	2.3	-67.0693	18.2257	23.5	2.9
c	1998	11	11	8	29	19.3	-67.0880	18.2212	27.8	3.3
d	1997	9	24	2	18	51.2	-67.1051	18.1448	26.0	2.5
d	1994	11	29	4	5	33.5	-67.0665	18.1532	26.6	3
d	1976	3	6	4	55	35.0	-67.0328	18.1397	25.1	2.4
e	1988	4	29	6	49	42.6	-67.1013	18.0937	23.7	2.4
e	1999	5	21	1	56	54.0	-67.1418	18.0904	25.1	2.4
e	1993	2	11	9	0	18.5	-67.1236	18.0698	22.4	2.2
f	1999	10	8	0	11	41.1	-67.0894	18.1349	24.0	2.2
f	1999	7	26	0	8	47.7	-67.0399	18.1434	23.7	2.3
f	1993	5	31	12	54	46.8	-67.0119	18.1365	24.2	2.1
g	1998	2	18	8	29	57.6	-66.8908	18.1454	23.8	2.2
g	1998	4	10	12	31	38.0	-66.8504	18.1506	24.3	2.4
h	1998	6	18	14	42	22.9	-66.6975	18.1261	23.0	2.1
h	2000	4	20	13	12	10.5	-66.7414	18.1153	22.8	2.1
h	1996	9	27	8	42	52.8	-66.6868	18.1192	22.5	2.2
i	1998	7	28	17	9	52.8	-67.0122	18.0682	22.4	1.9
i	1996	11	5	20	36	31.3	-67.0013	18.0684	22.5	2.2
i	2000	3	28	5	32	29.3	-67.0561	18.0892	27.8	2.4
i	1994	12	4	22	47	27.9	-67.0273	18.0507	20.5	2
i	1999	12	3	8	25	56.5	-66.9338	18.0845	21.5	2.3
i	2000	2	9	18	53	23.4	-66.9454	18.0826	25.1	2.5
i	1992	6	24	0	11	1.0	-66.9421	18.0577	18.9	2.1
i	2000	8	31	14	28	19.3	-66.9452	18.0600	23.4	2.3
j	2000	12	4	17	46	55.3	-67.0449	18.0730	21.1	2.1
j	1996	7	9	19	24	31.4	-67.0347	18.0732	21.3	2.6
j	1992	9	3	3	3	50.1	-67.0512	18.1127	19.1	2
k	2001	2	19	13	17	40.8	-66.0744	18.0958	26.5	2.7
k	1988	8	29	13	58	11.2	-66.0342	18.0727	27.4	2.4

k	1998	6	19	0	0	57.0	-66.0848	18.0794	23.6	2.6
k	1996	6	15	10	48	36.4	-66.0979	18.0852	23.1	2.6
l	1977	1	7	21	52	37.0	-66.0112	18.1067	18.2	1.5
l	1977	1	8	6	8	37.5	-66.0212	18.0856	23.1	1.1
m	1998	1	19	23	12	9.7	-66.6557	18.1269	21.2	2
m	1998	8	12	3	8	13.2	-66.6716	18.1708	23.9	2.4
m	1996	8	30	12	43	6.0	-66.7175	18.1496	23.2	2.1
m	1997	4	15	8	32	32.7	-66.7289	18.1333	23.7	2.4
m	2001	5	11	16	23	14.3	-66.7310	18.1504	20.4	2
n	1996	3	13	7	41	34.8	-66.7974	18.0042	19.3	2.3
n	1996	3	13	9	9	37.4	-66.7938	18.0036	20.4	2.3
n	1996	3	13	9	18	40.2	-66.7980	17.9999	19.6	2.3
n	1996	3	13	19	29	30.1	-66.7926	18.0207	18.9	2.3
n	1996	3	13	19	56	59.3	-66.7969	17.9999	19.1	2
n	1996	3	13	21	12	15.7	-66.7938	18.0042	19.3	2.1
n	1996	3	13	21	24	2.9	-66.7965	17.9986	20.0	2.4
n	1996	3	14	0	51	57.5	-66.7950	18.0054	19.0	2.3
n	1996	3	14	6	44	6.9	-66.7969	18.0026	19.7	2.6
n	1996	3	14	7	4	14.8	-66.7965	18.0036	19.1	2
n	1996	3	14	8	6	57.7	-66.7974	18.0078	19.8	2.3
n	1996	3	14	14	38	49.1	-66.7978	18.0052	19.1	2.3
n	1996	3	14	15	16	26.4	-66.7972	18.0001	19.6	2.5
n	1996	3	14	19	57	26.6	-66.7985	18.0053	19.3	2
n	1996	5	26	6	1	22.0	-66.7964	18.0048	19.1	2
n	1996	6	27	5	24	54.8	-66.7963	18.0030	19.6	2.3
p	1976	3	15	0	54	53.2	-67.0955	17.9890	16.0	1.1
p	2000	6	8	6	26	32.6	-67.1109	18.0046	15.6	2.1
p	1998	2	25	23	6	45.5	-67.0772	18.0073	18.3	1.8
p	1998	2	26	0	22	41.7	-67.0941	17.9937	20.0	2
o	1996	4	6	2	58	52.2	-67.1302	17.9935	17.0	2.2
o	1996	4	6	19	37	13.9	-67.1253	17.9945	17.0	1.8
o	1996	1	29	13	42	37.8	-67.1163	17.9947	16.2	2.1
o	1997	1	5	21	25	52.3	-67.1236	17.9953	17.8	2.1
o	1998	3	1	1	11	24.7	-67.1211	18.0046	18.0	1.9
o	2000	5	15	4	48	47.3	-67.1311	17.9918	16.8	2.2
o	2001	3	22	22	6	19.6	-67.0721	17.9776	16.2	1.8
q	1997	5	29	9	1	59.8	-67.0708	18.1948	29.4	2.4
q	1995	3	14	3	45	23.8	-67.0326	18.1928	29.5	2.7
q	1996	2	29	23	27	19.0	-67.0714	18.1982	29.5	2.7
r	1994	3	1	0	16	0.3	-66.3830	18.2453	38.4	3.6
r	1999	5	14	23	16	14.8	-66.4565	18.2306	34.8	3
s	1996	12	30	23	29	29.7	-67.0228	18.1699	28.1	3

s	1996	2	29	4	29	25.7	-67.0729	18.1840	32.1	3.5
t	1996	2	29	16	42	53.2	-67.0838	18.1889	31.9	2.7
t	1996	2	29	4	39	30.0	-67.0652	18.1881	29.3	2.6
u	1991	12	16	10	29	33.9	-67.0685	18.1788	30.8	2.5
u	1996	4	25	17	18	33.3	-67.0773	18.1792	31.6	2.7
v	1996	2	29	4	56	39.1	-67.0628	18.1977	29.7	2.9

On following pages- Figure 5a-v Focal Mechanisms with first motions, nodal planes, P and T axes, lower hemisphere projection. Filled circles are compressions, open circles are dilitations.

A



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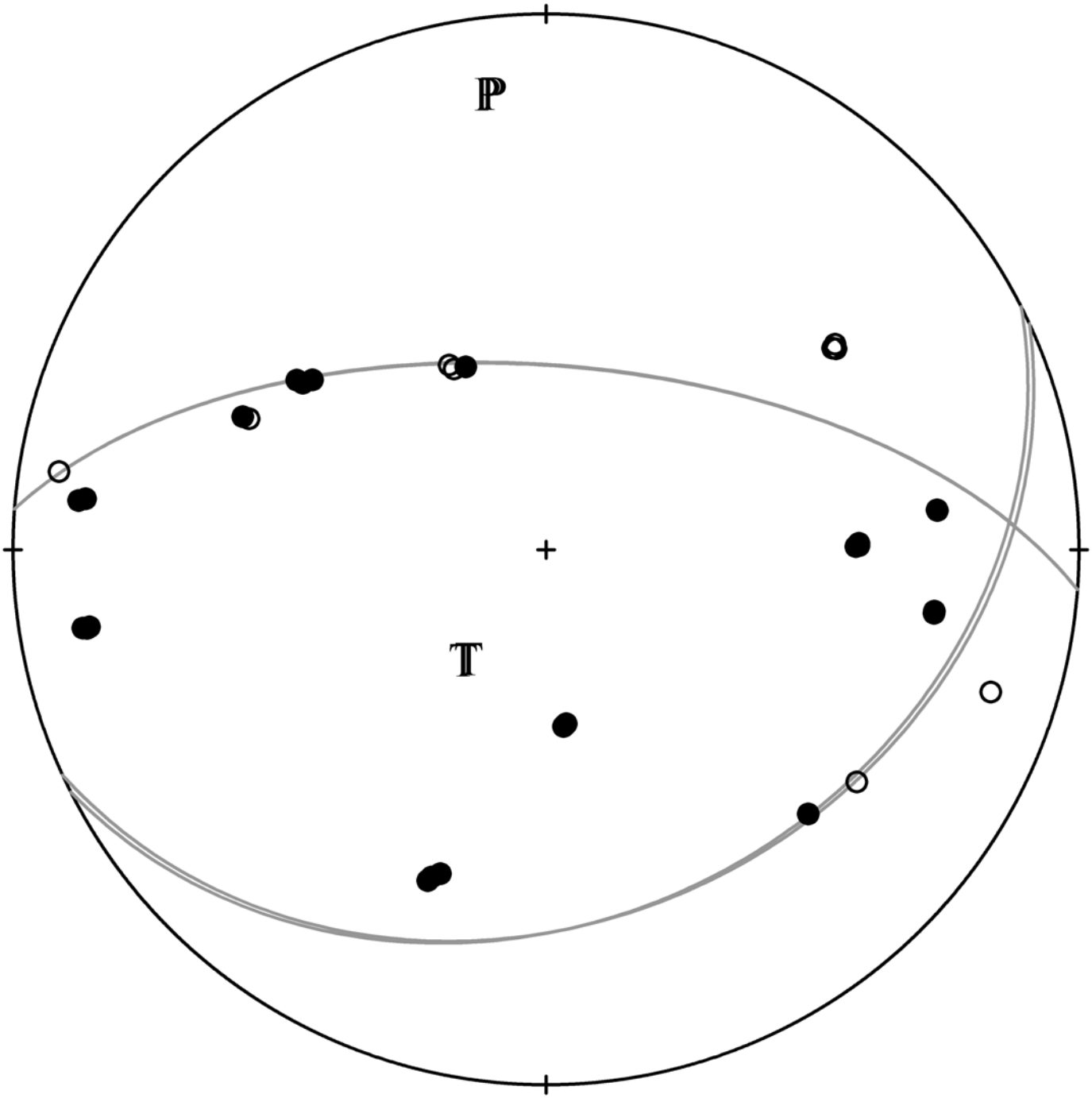

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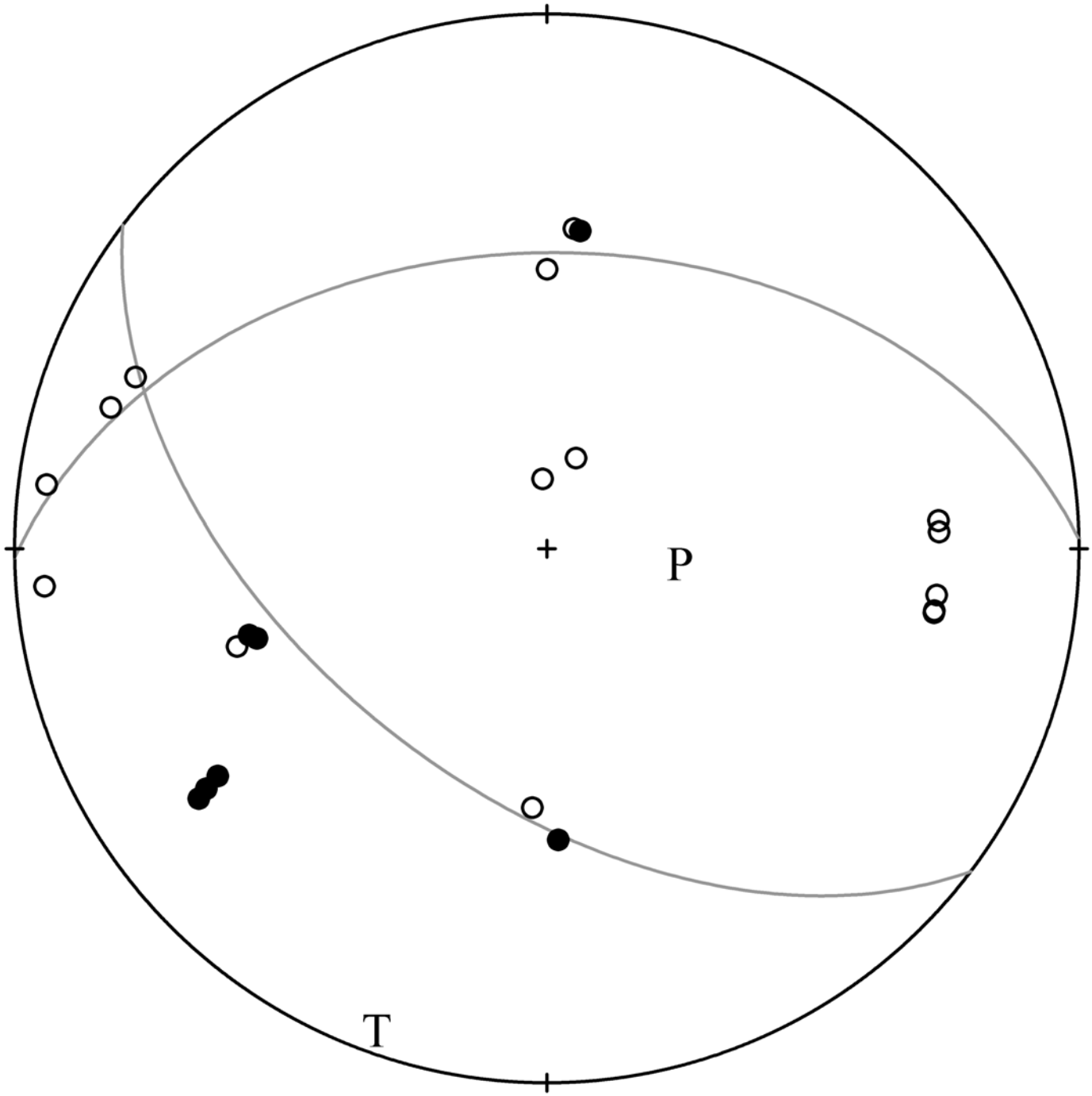

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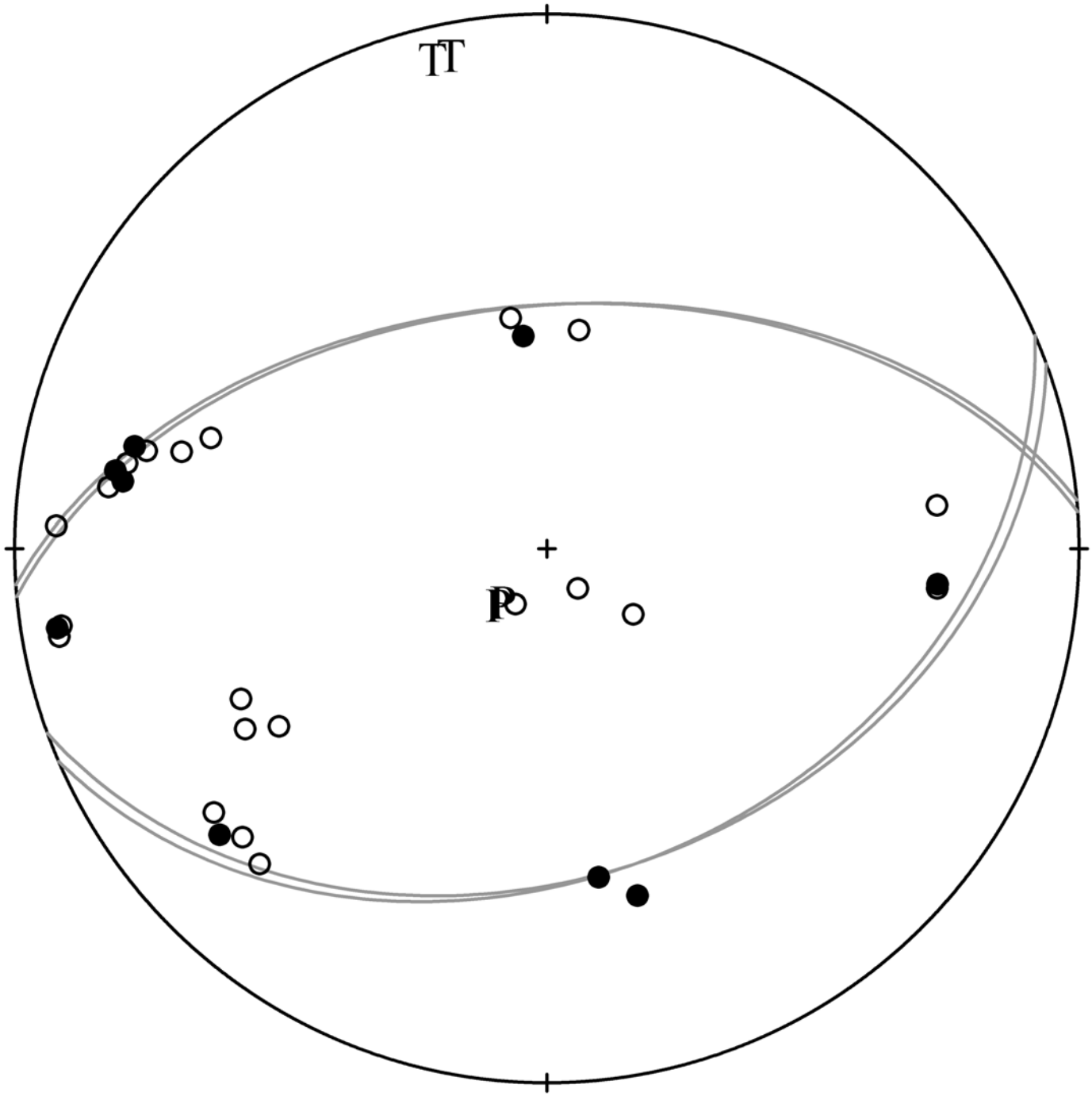

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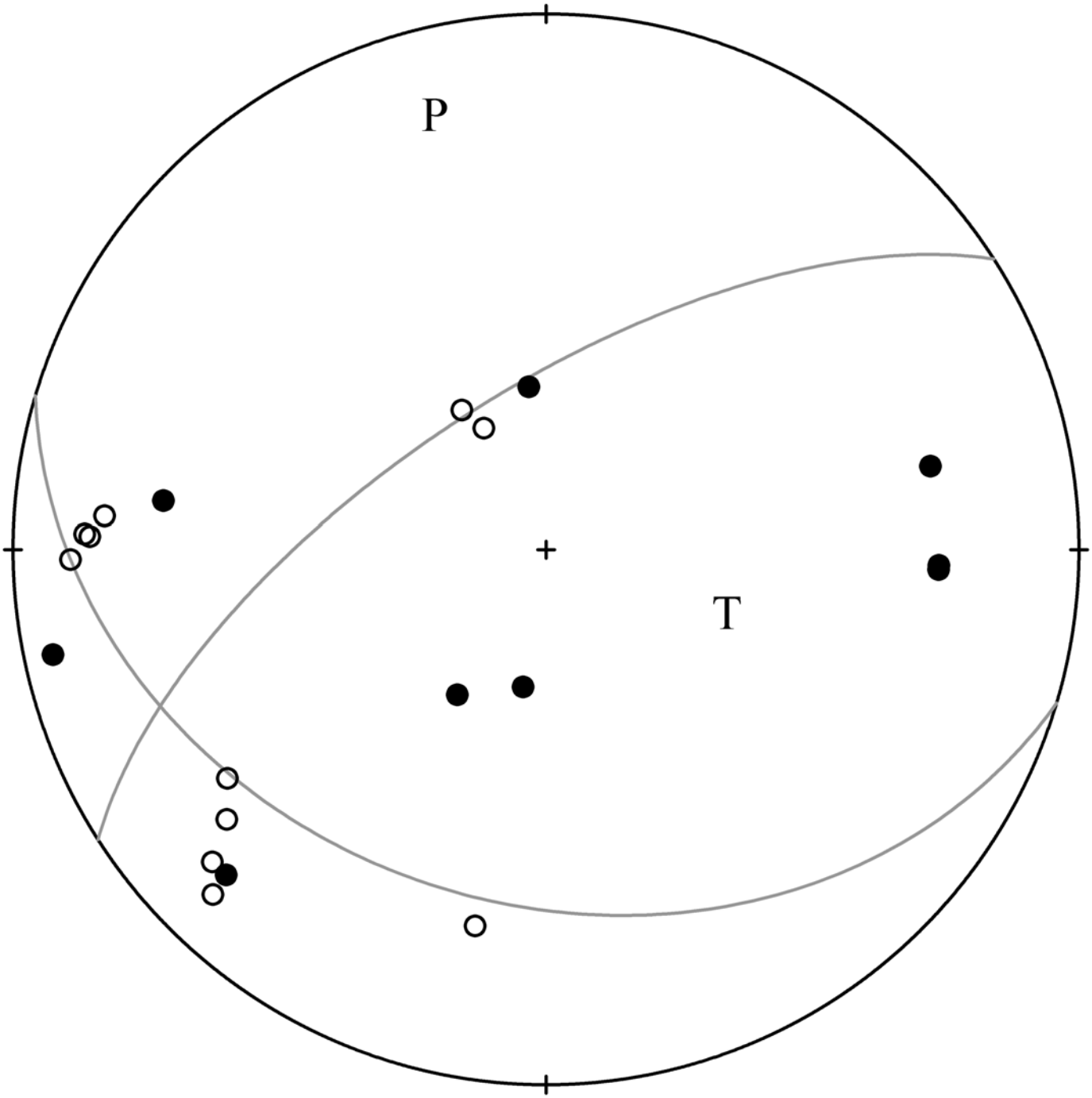

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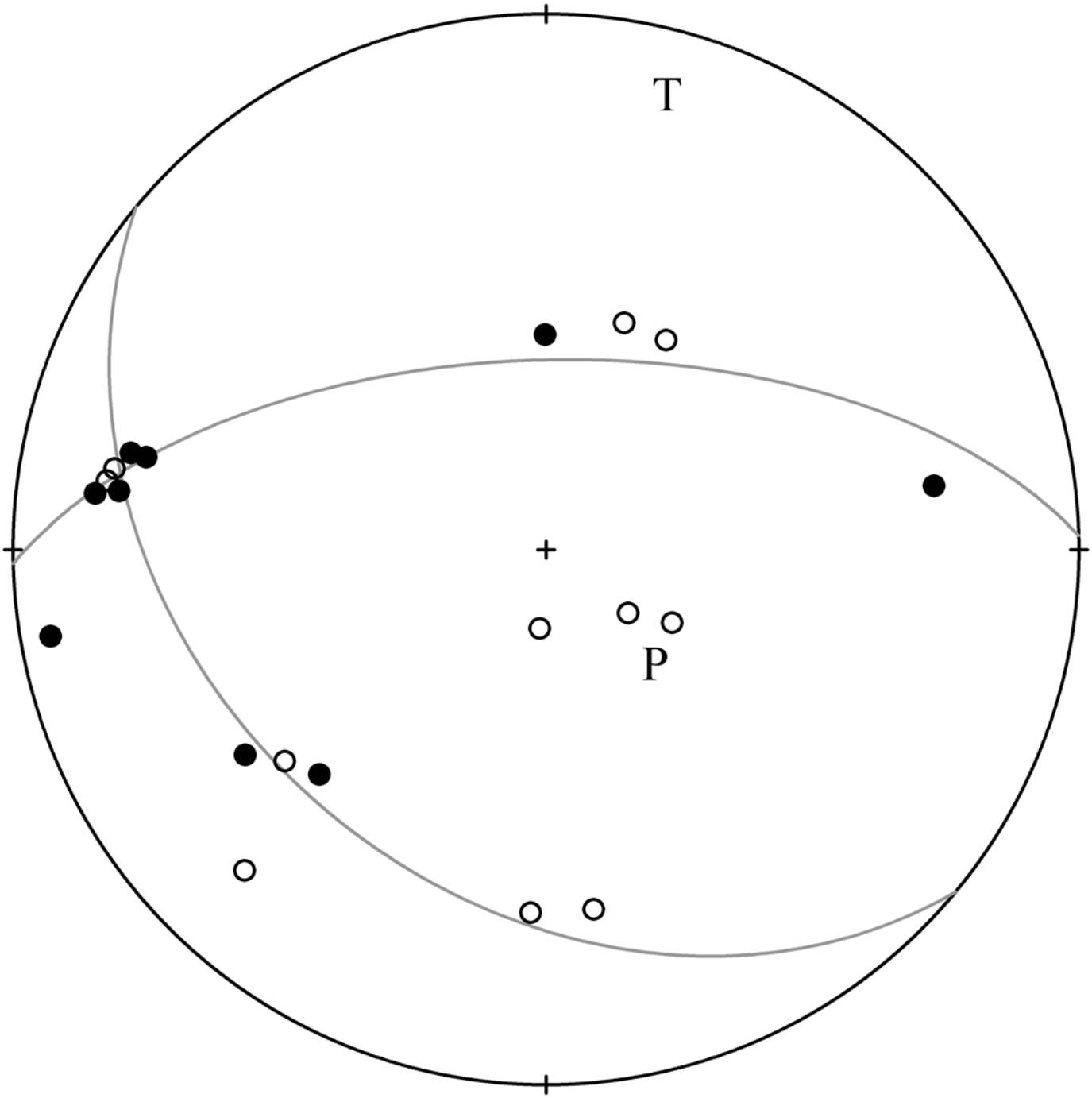

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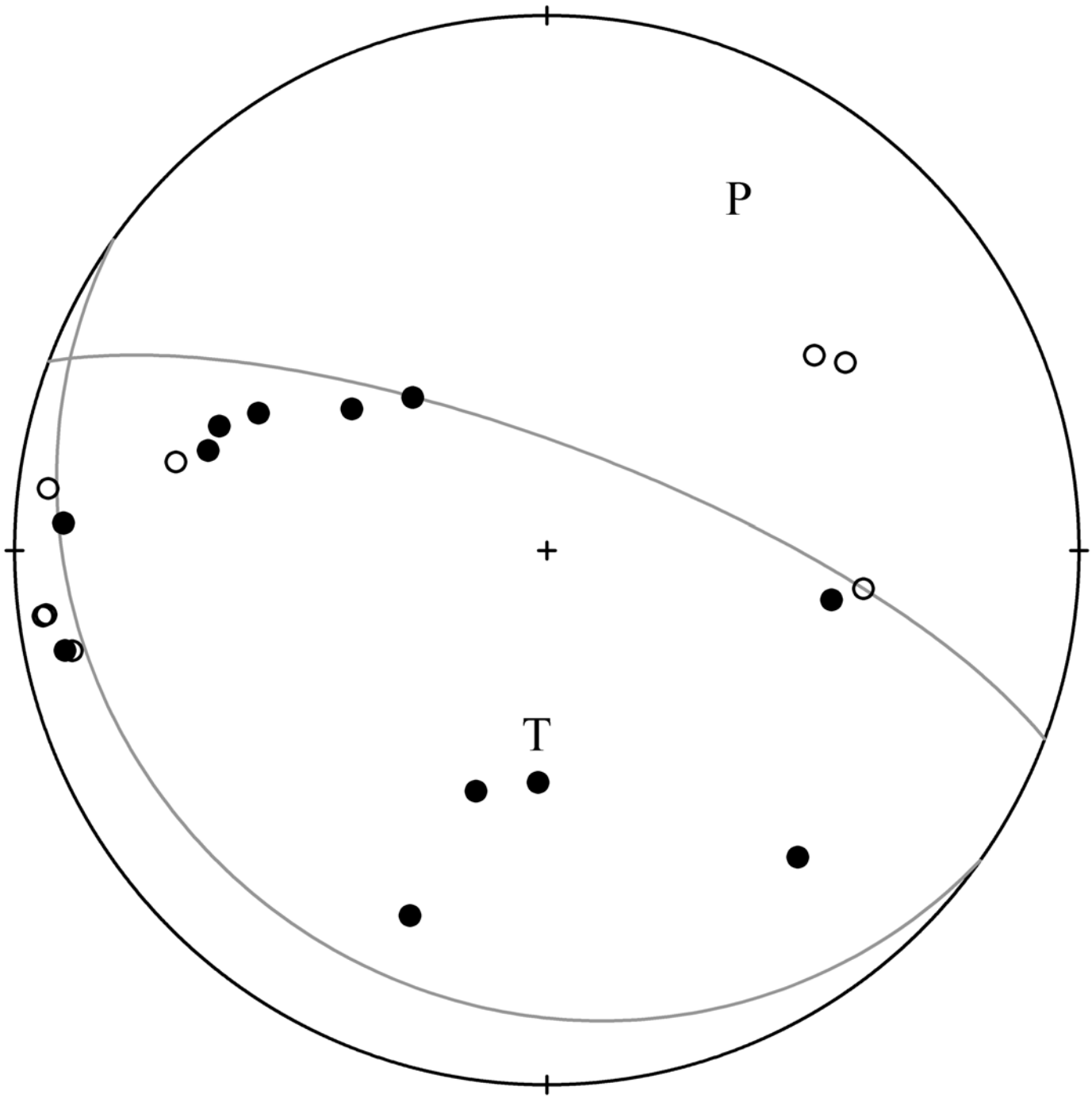

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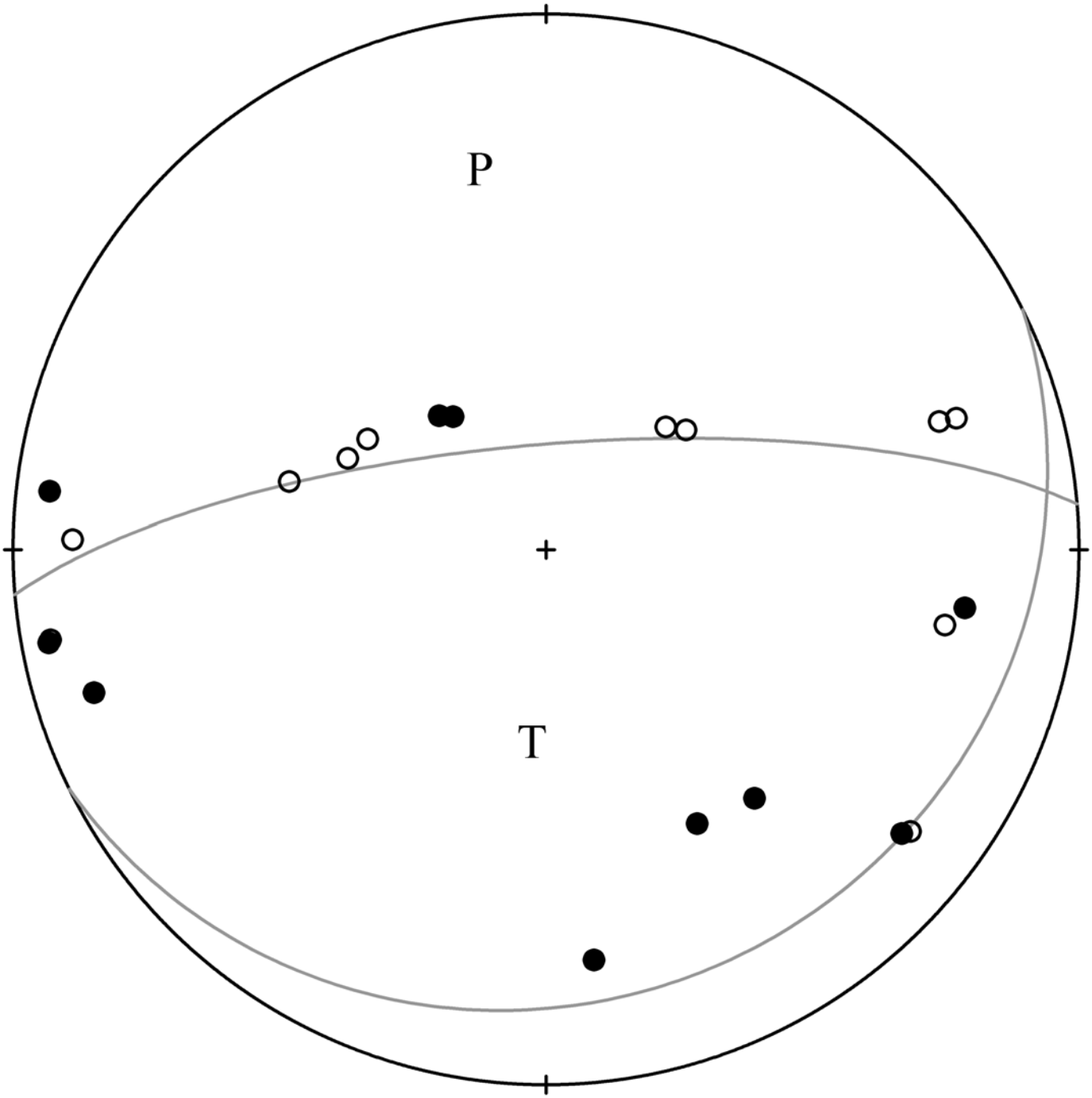

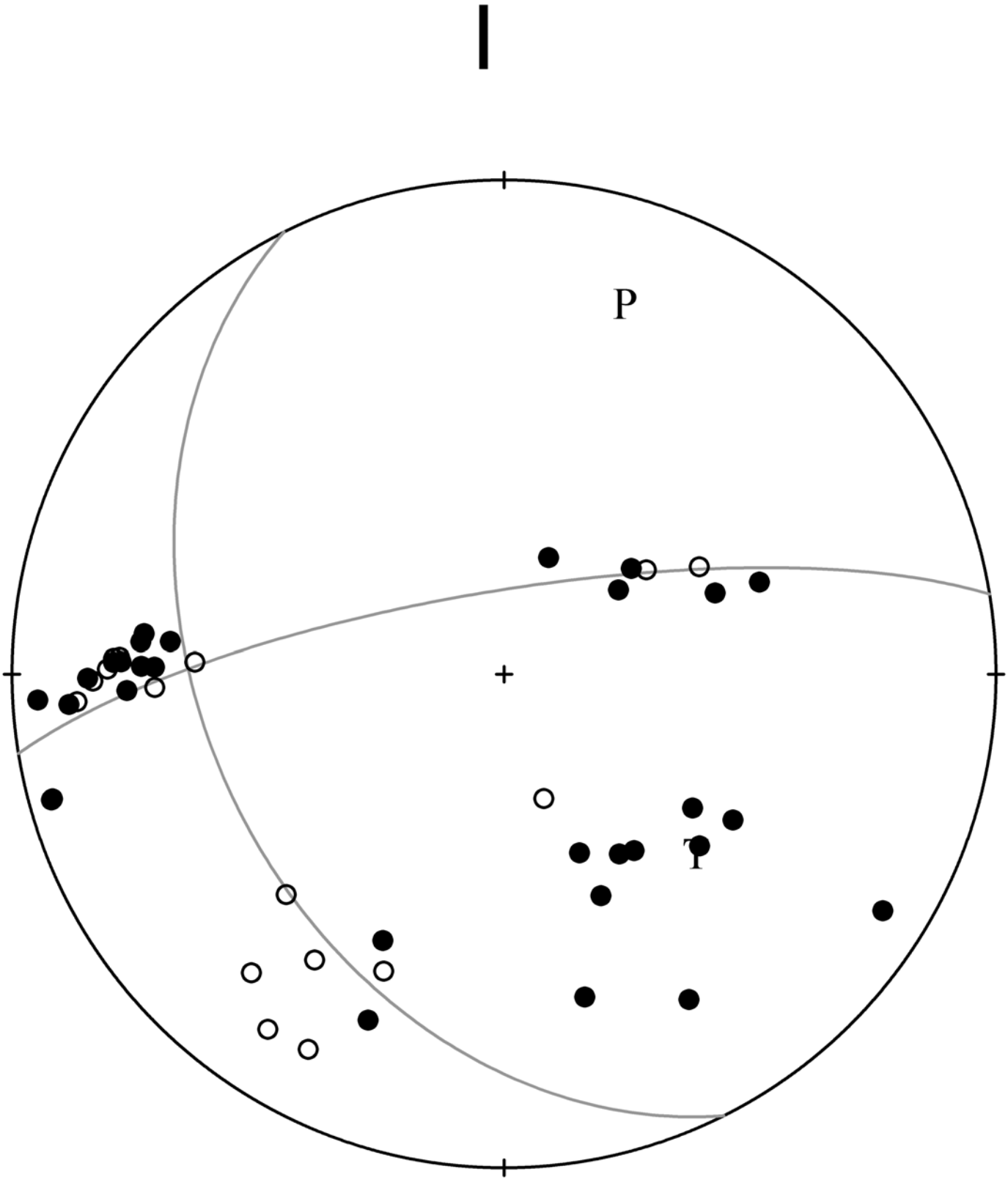
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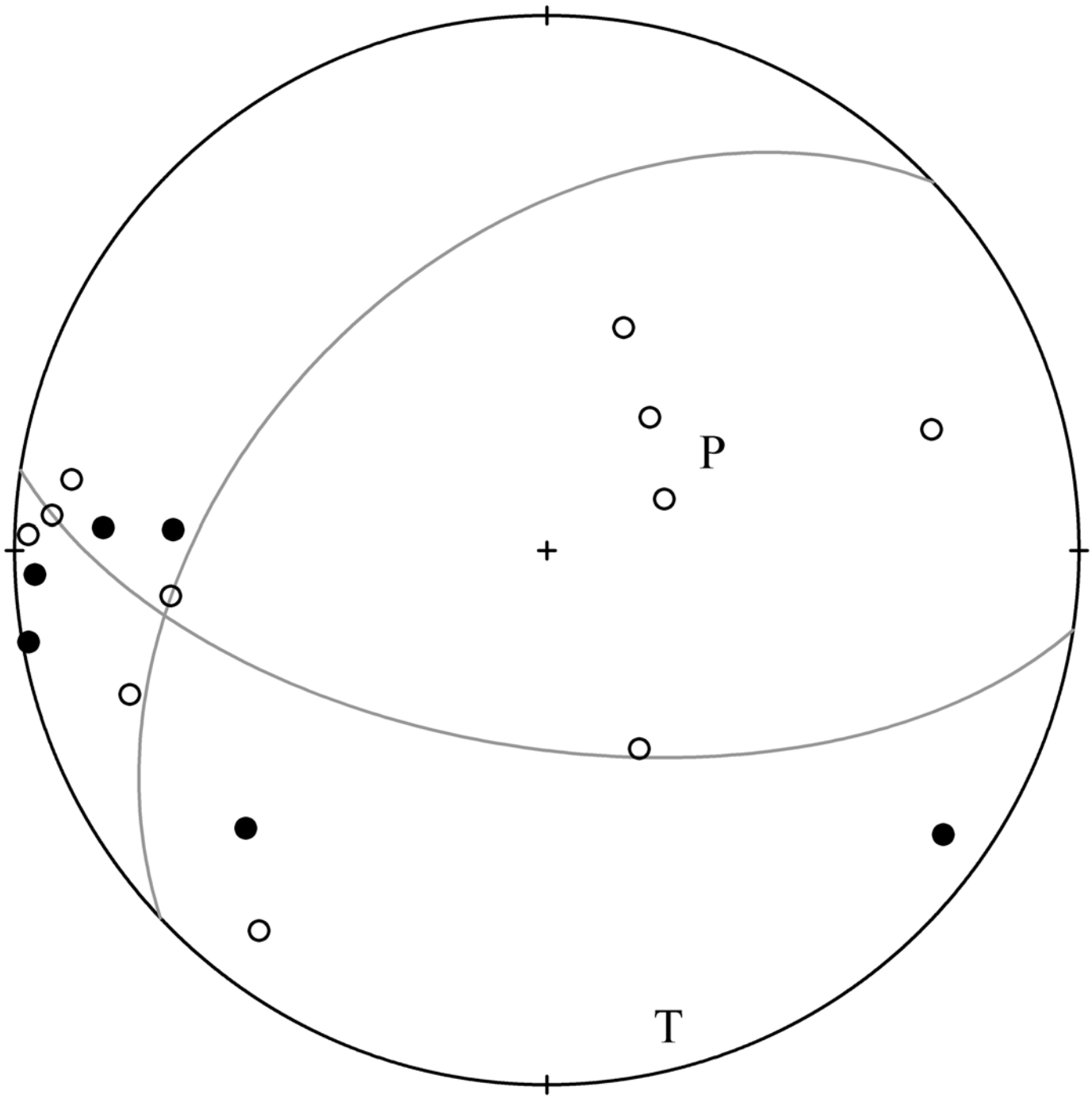

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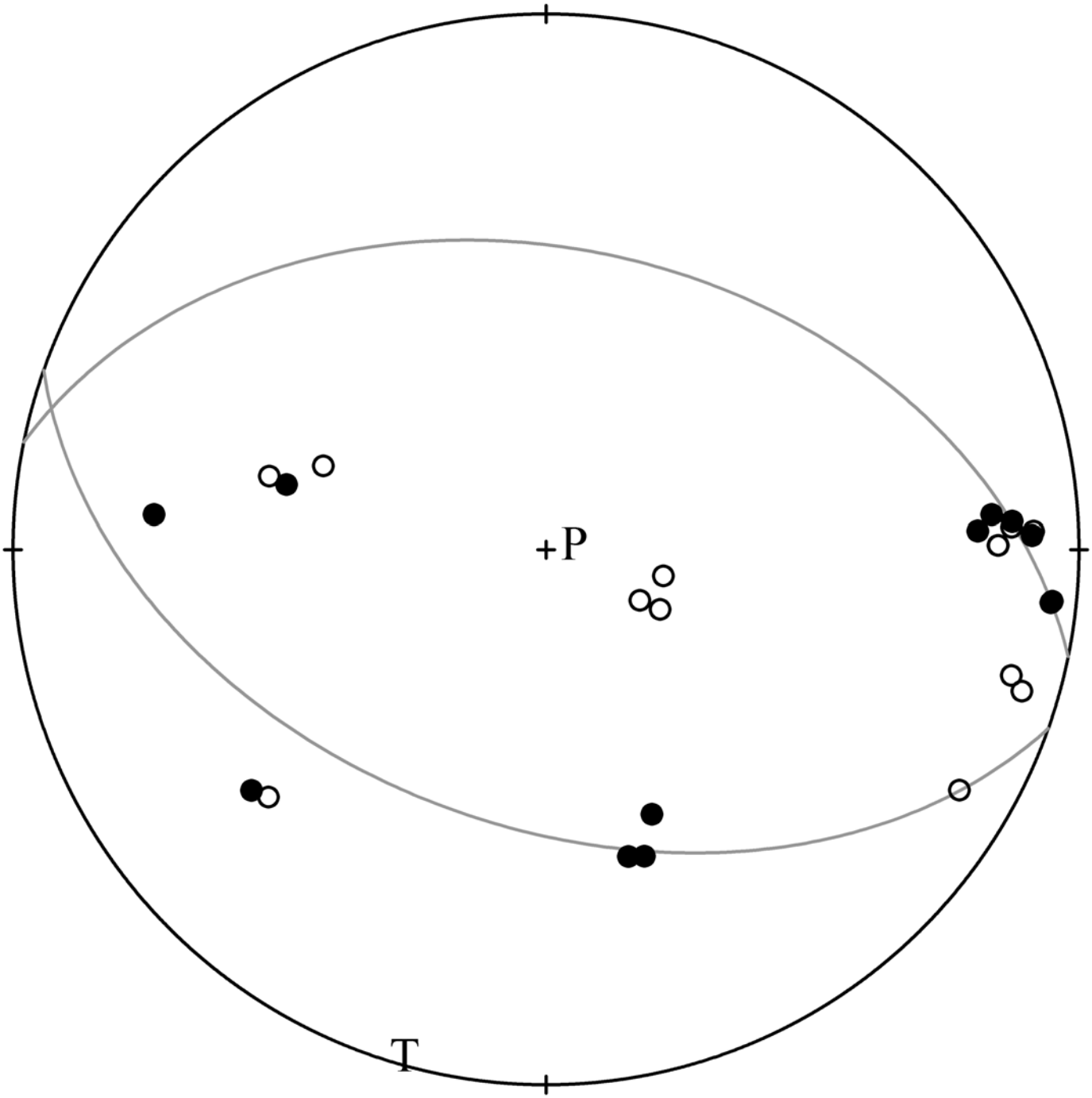

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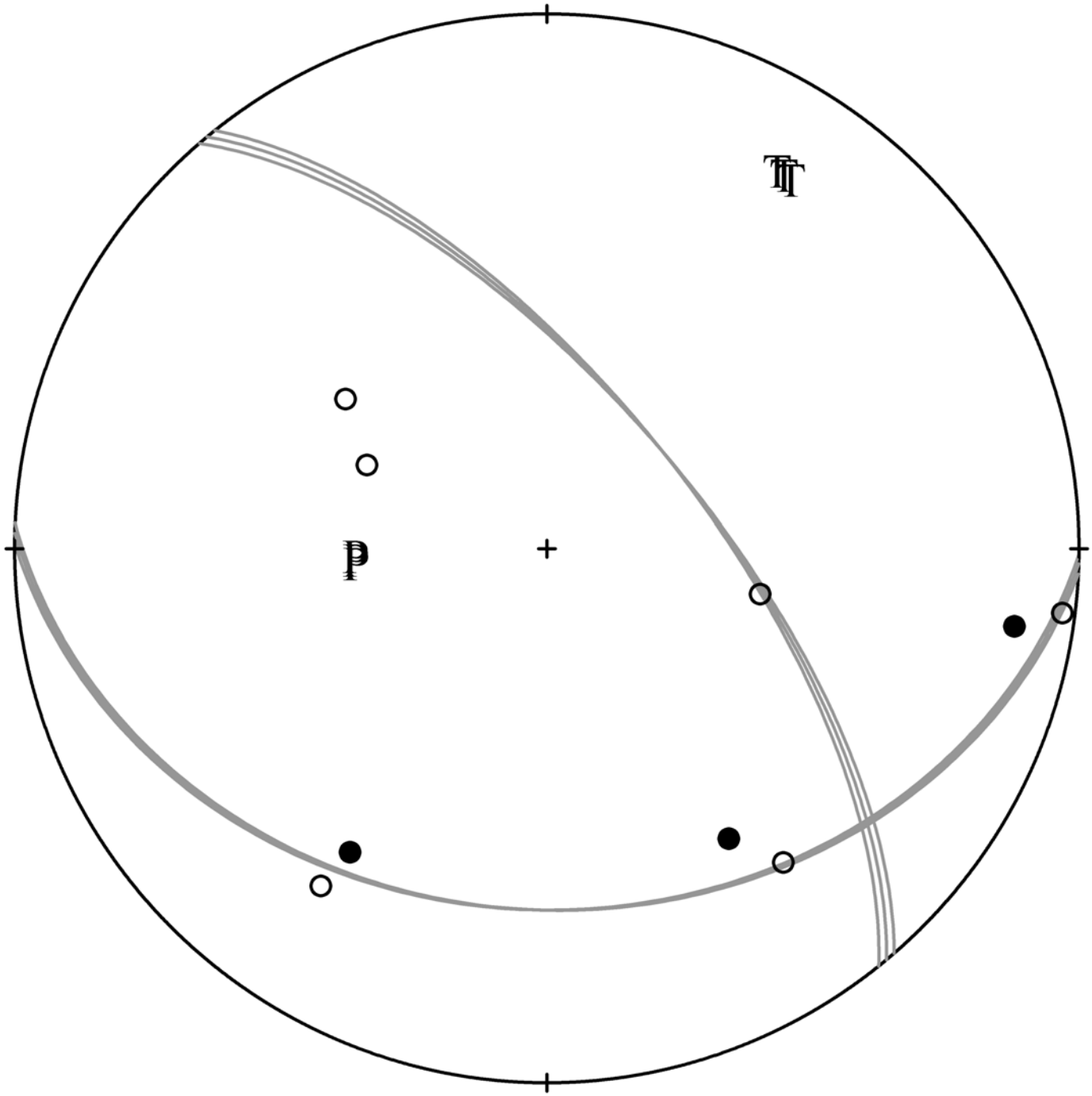

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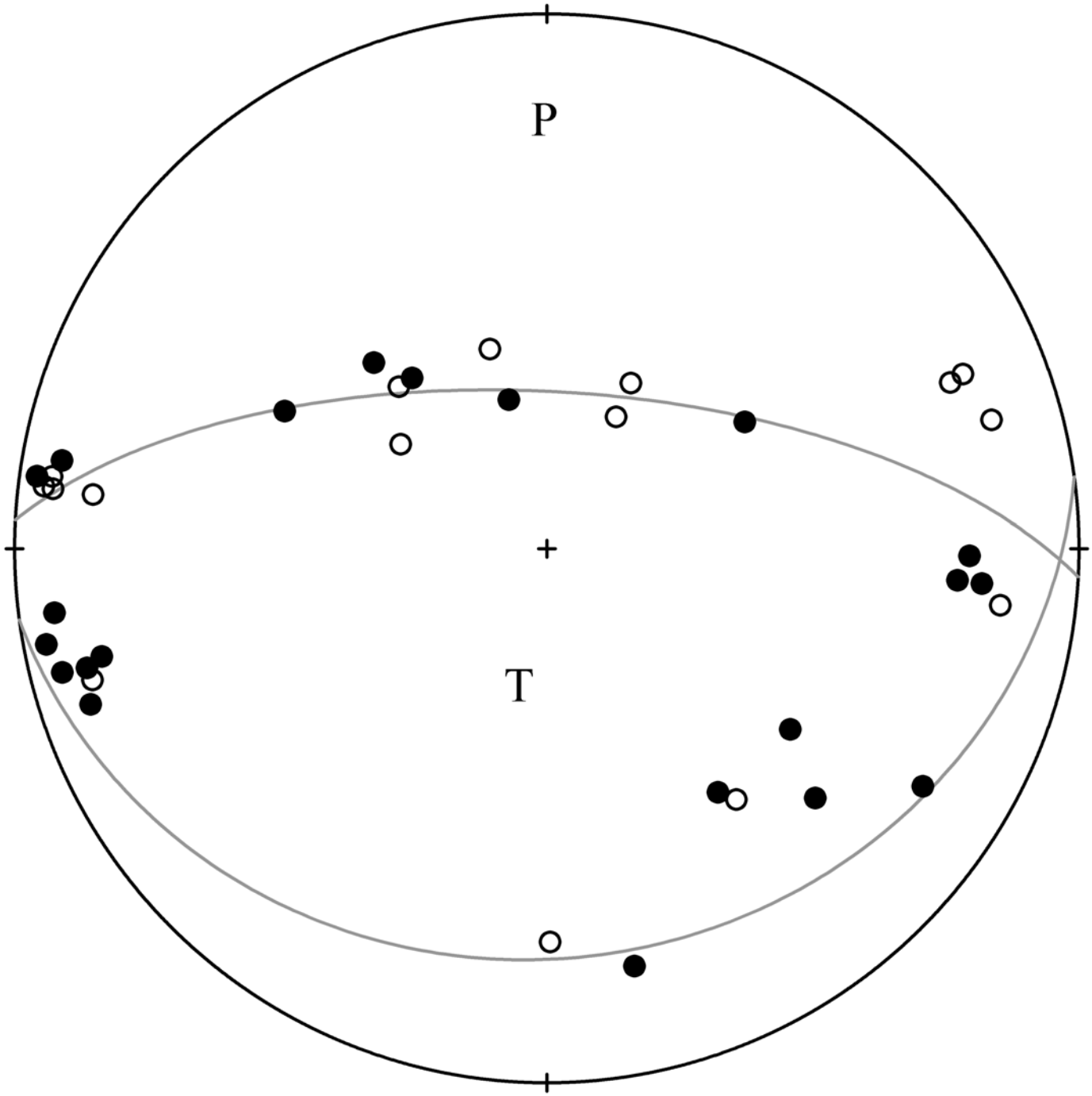

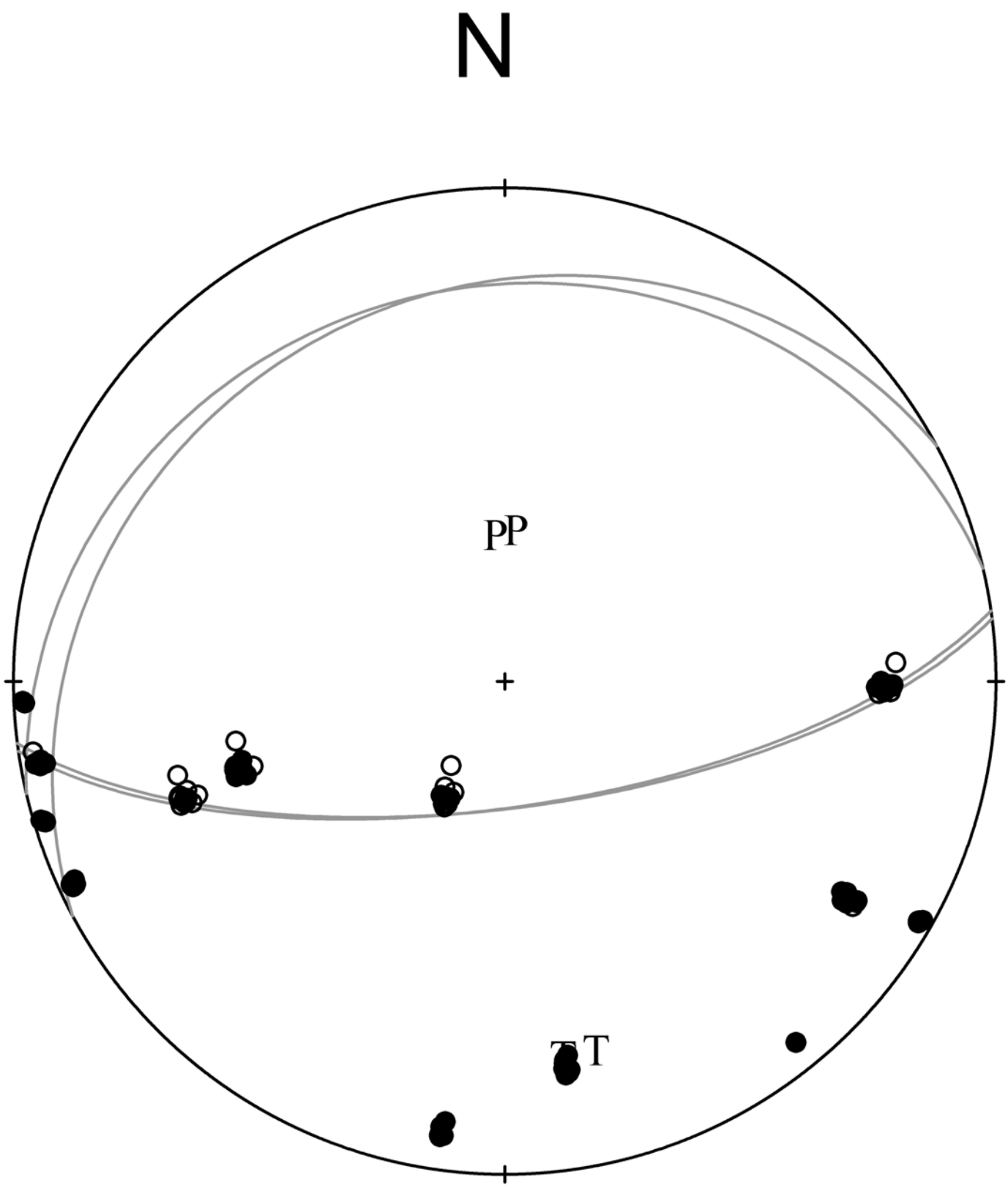
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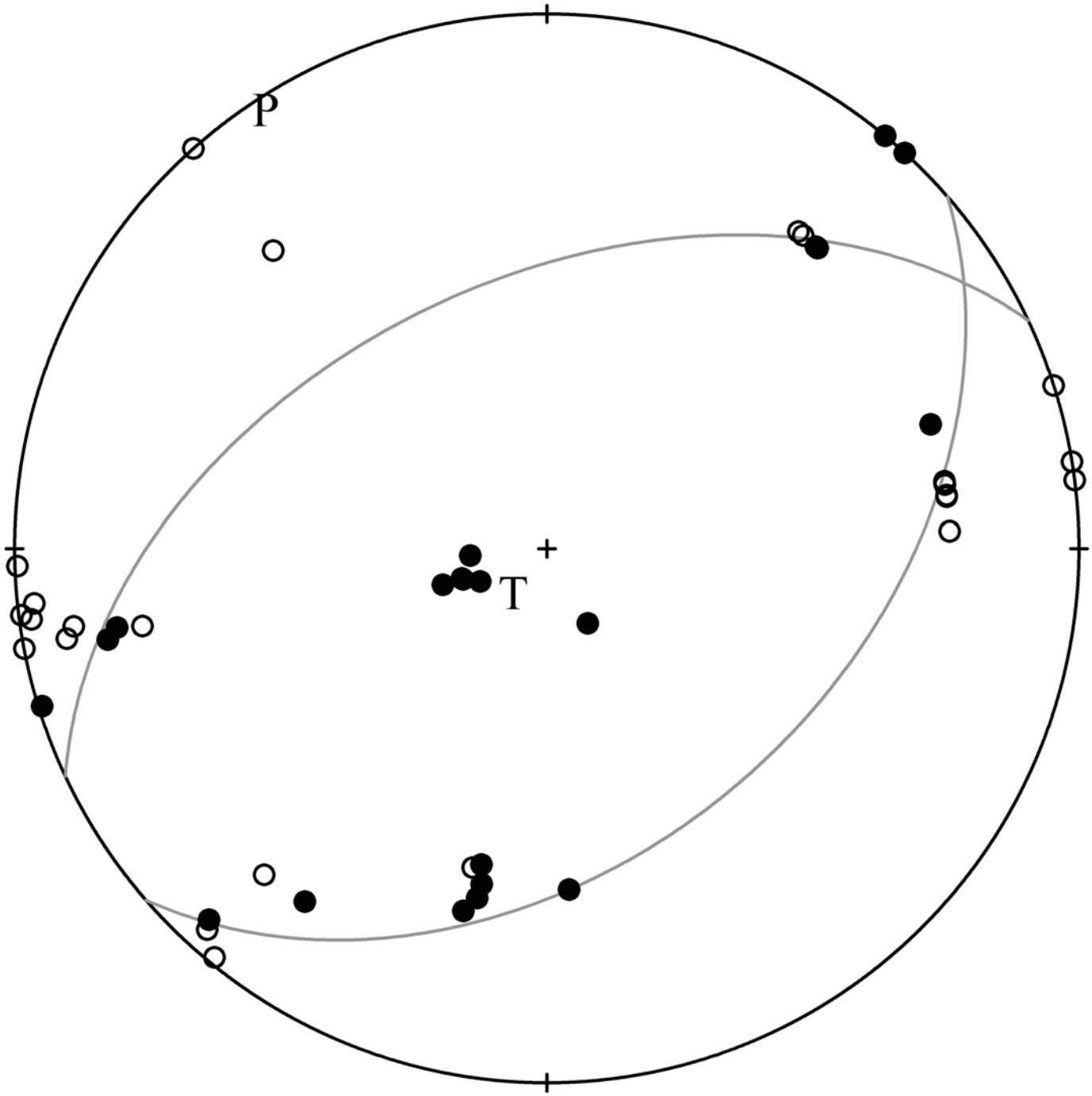

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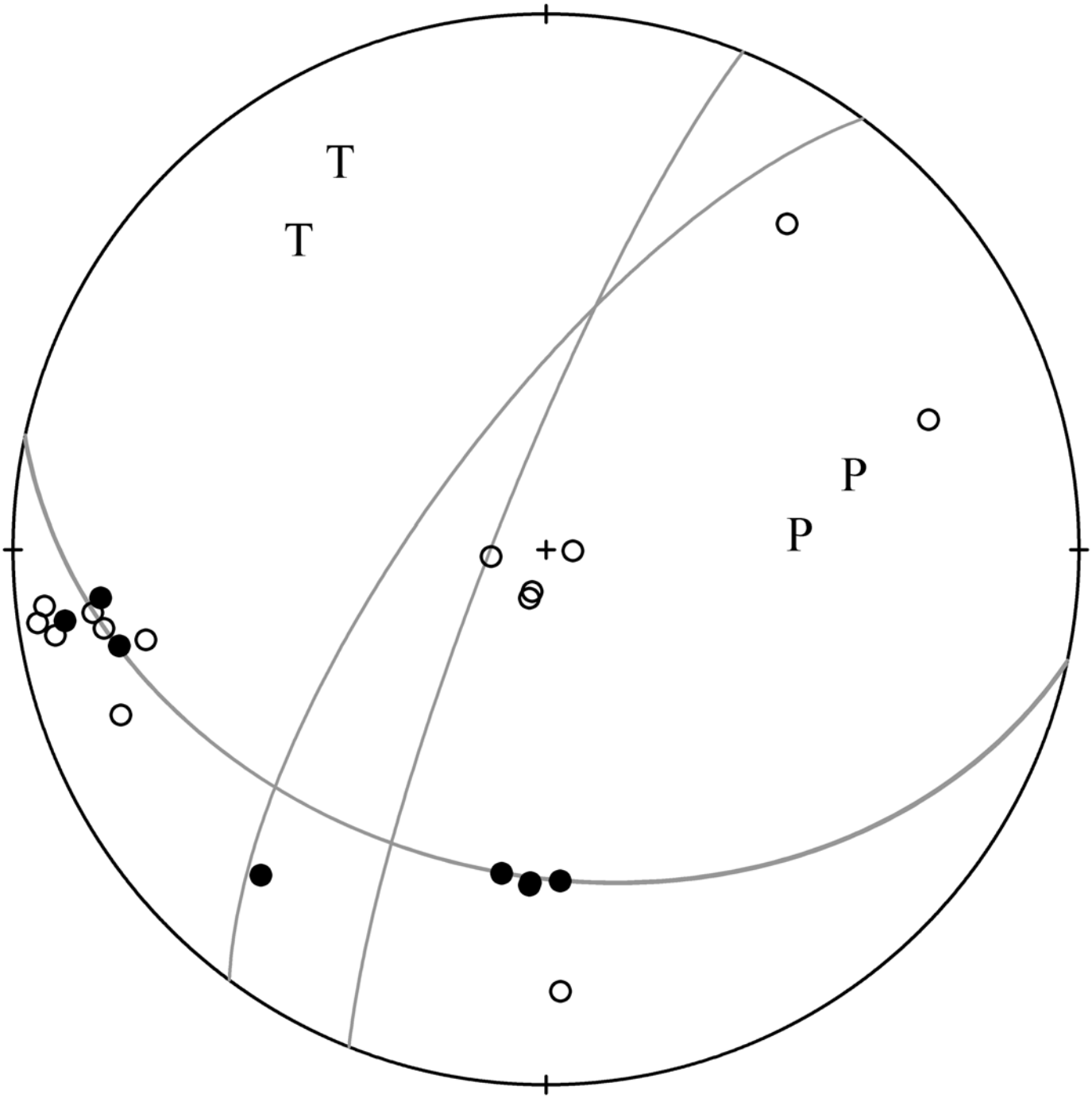

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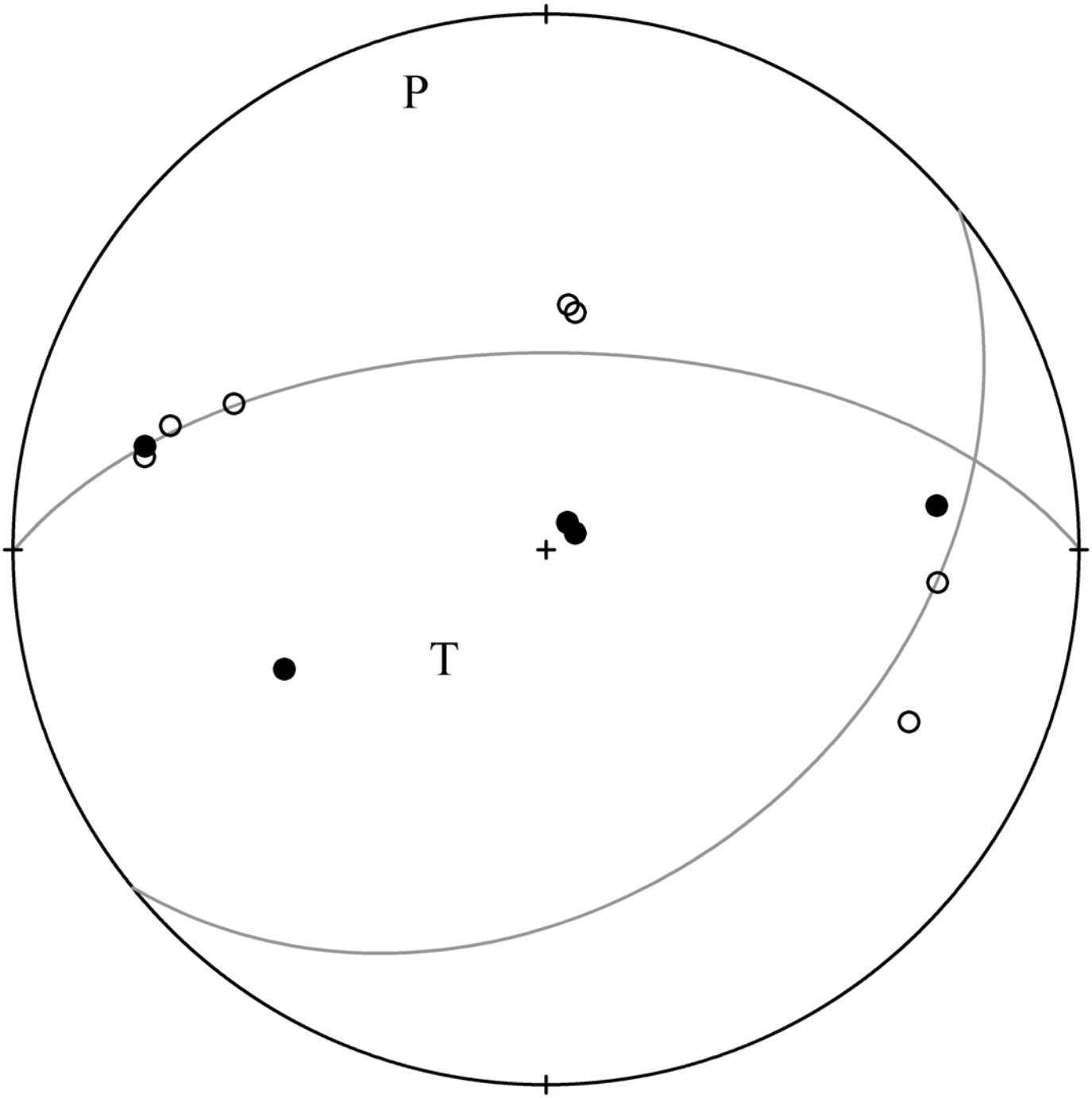

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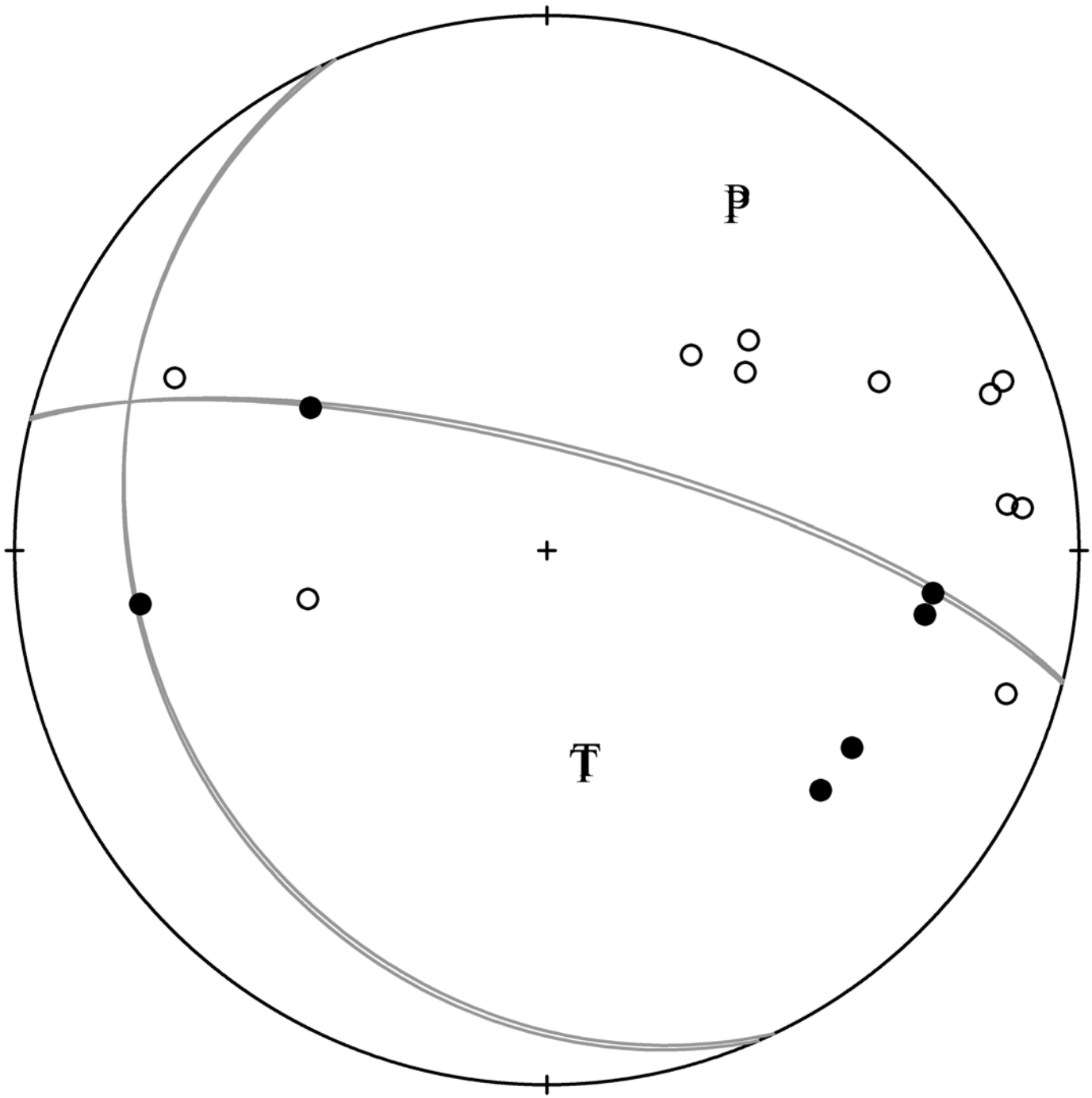

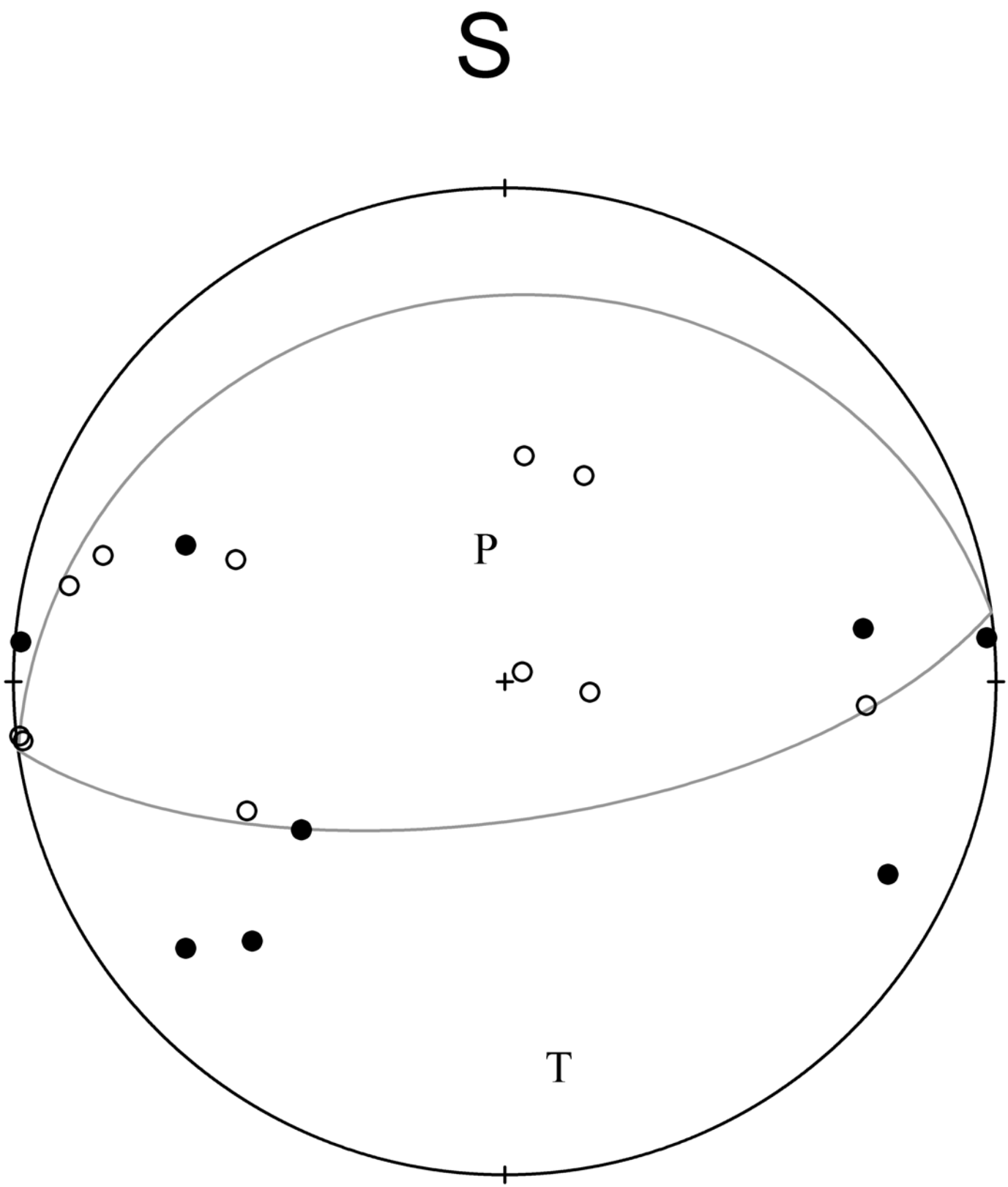
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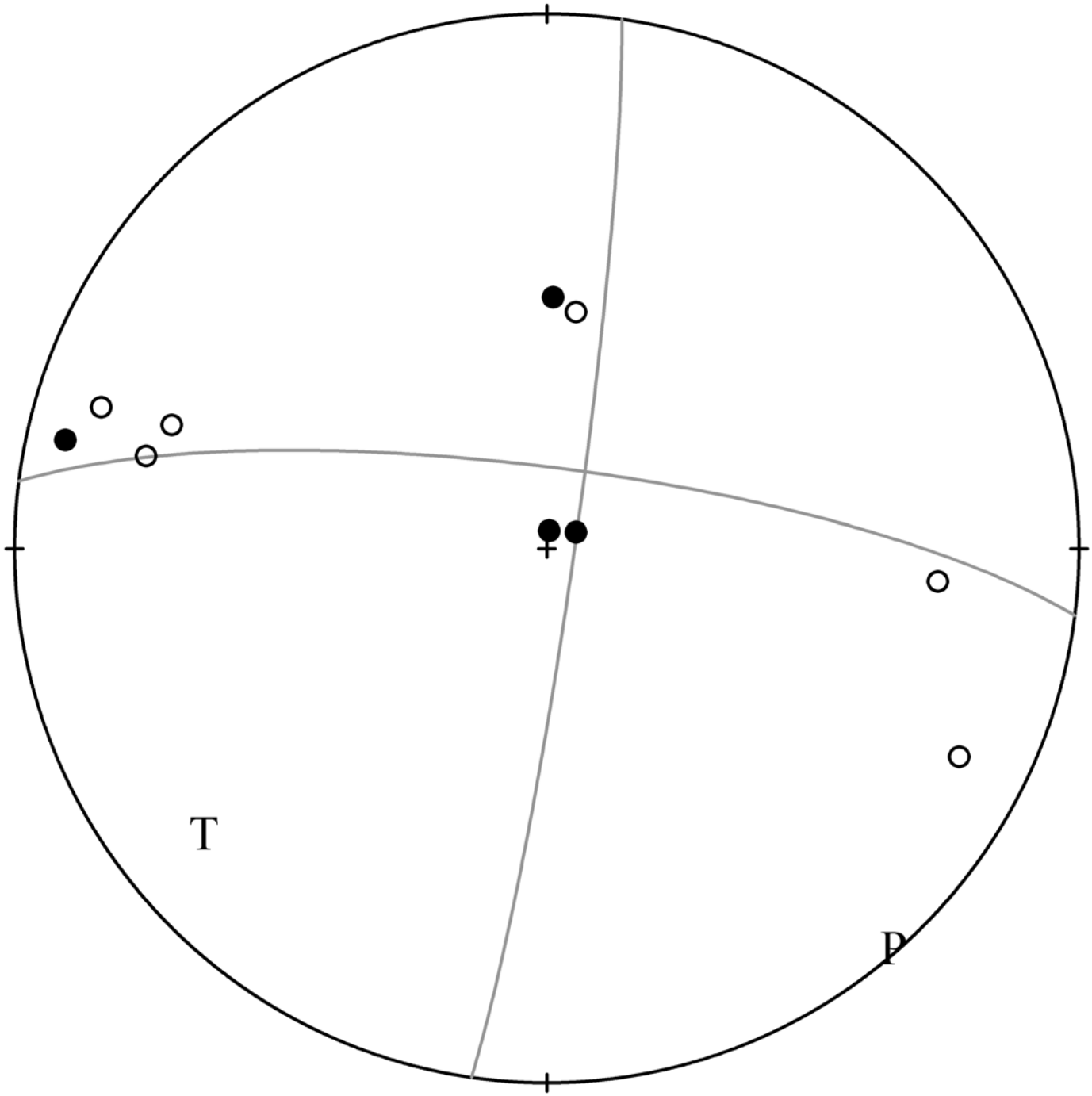

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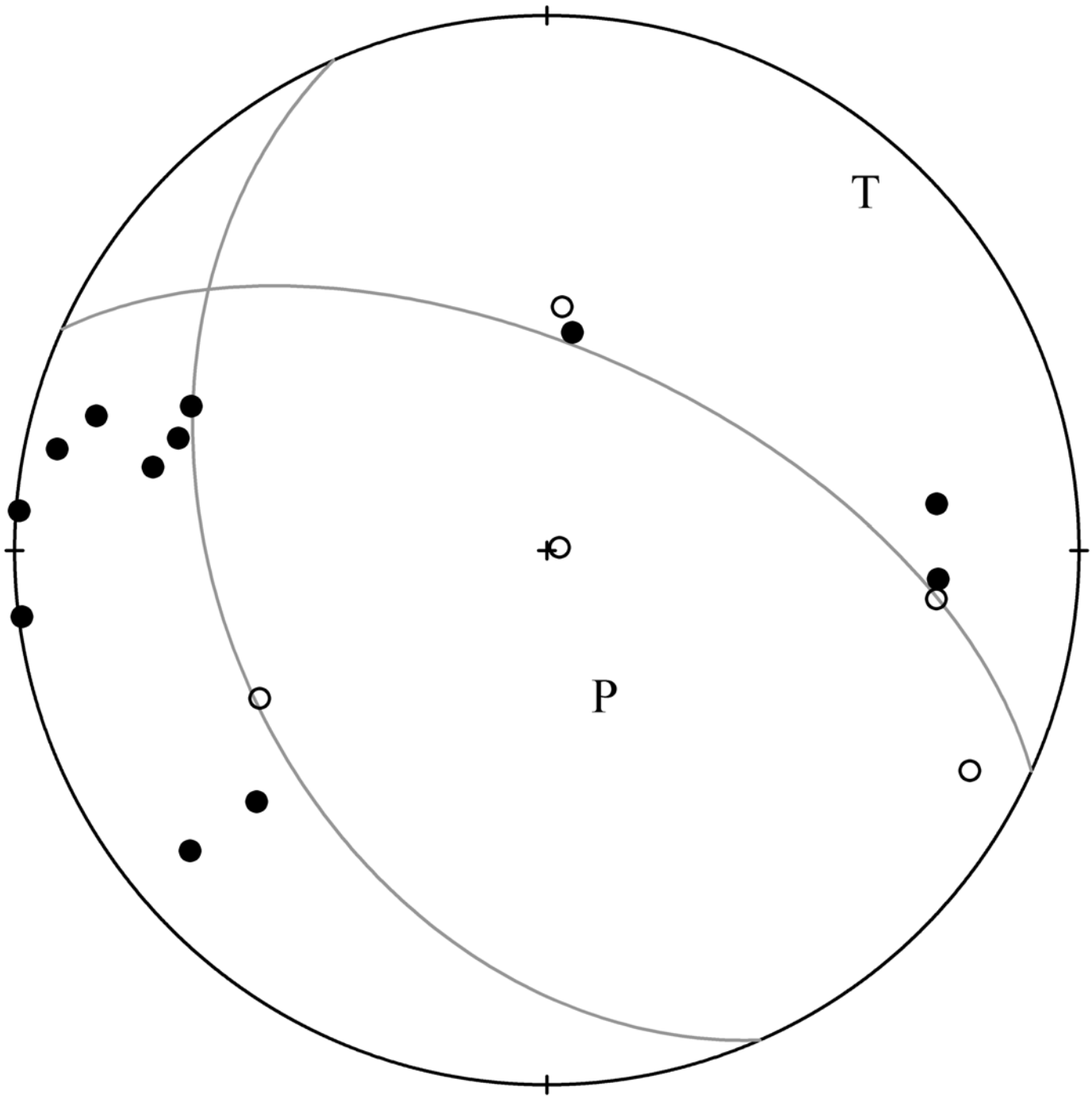

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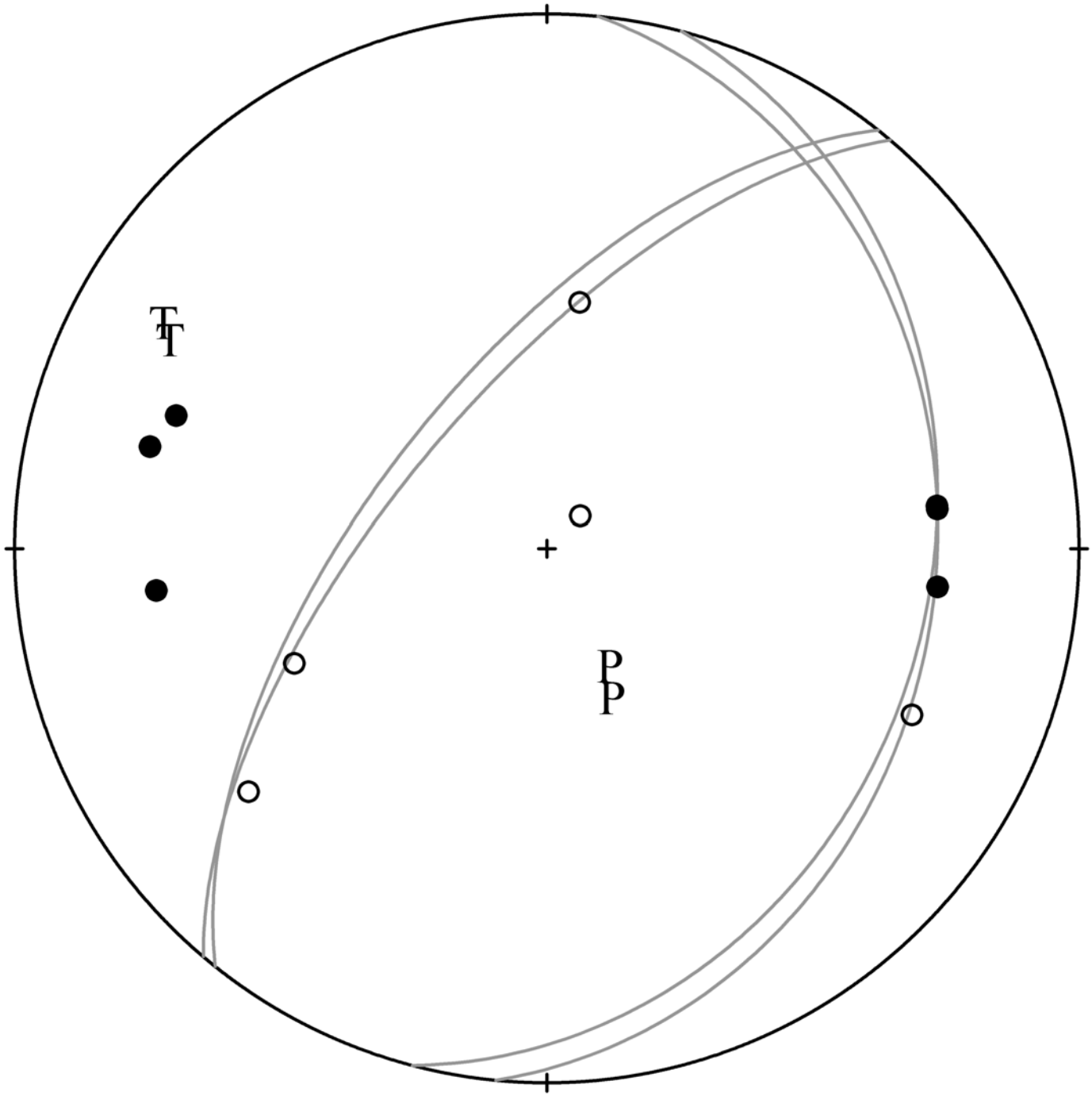

Discussion of Results

The DD relocation process results in a much better definition of the downgoing seismic zone. It is clearly a northerly dipping surface that increases its dip with depth. The Muertos Megathrust lies at about 10 below the surface at the latitude of the south coast of Puerto Rico and some 30 km beneath the center of the island where the seismicity stops. It is well defined from the westernmost part of the island near the edge of the network and for about 50-75 km to the east. East of 66.5ºW gaps in seismicity inhibits an easy interpretation.

The simplest tectonic interpretation for this region is that the Caribbean plate has been obliquely sliding beneath Puerto Rico for 10's of millions of years. It would descend beneath the overriding plate far to the west beneath Hispaniola and continue sliding eastward and gently northward and deeper into the subduction zone. Thus a subducted slab is more or less continuous along the entire length of the Muertos Trough. As the Caribbean Plate is this region is part of the Caribbean Large Igneous Province, it is buoyant and resists subduction, thus the shallow angle of descent into the subduction zone. This shallow dip suggests that the megathrust is strongly coupled.

Variations in observed seismicity might be related to motions of the microplates overriding the Caribbean slab, and changes in the thickness of the upper plate. The Puerto Rico microplate experienced a collision with the Bahama Bank along its northern margin ending about 5Ma. That interaction caused the microplate to rotate about 25º counterclockwise (Reid at al., 1993) and that differential overthrusting of the Caribbean could have accommodated rotation plate, which lay all along its southern margin. This would be a short-lived arc polarity reversal, thrusting the western edge of the microplate over the Caribbean plate to a greater degree than farther east. The fact that more underthrusting occurred recently along the western PR microplate margin might explain the higher level of seismicity in western Puerto Rico. Thus, even if the Caribbean Plate is a continuous feature beneath all of southern Puerto Rico, some portions are presently essentially aseismic, reflecting a more tranquil tectonic environment over the last 10Ma.

In the western are higher levels of seismicity in particular event within the crust above the downgoing plate might reflect and interaction between the downgoing plate and upper plate deformation. In New Zealand, where the buoyant Hikurangi Plateau subducts beneath North Island, shortening of the overriding plate is directly related to the convergence of that buoyant body. In fact, a close spatial relationship has developed between kinks in the downgoing plate and deformation in the overriding plate. That is, high angle faulting on the downgoing plate creates snowplow effects, compressing the upper plate along imbricate thrusts as they move deeper into the subduction zone (Nicol and Beavan, 2003, Henrys et al., 2006).

The case for Puerto Rico would be more complicated because of the oblique nature of the convergence. Any along strike irregularity that might develop on the downgoing plate, such as those found in New Zealand, would induce uplift or depressions in the upper plate, but because of the sideways motion of such a buried feature, its surface expression might be oriented generally E-W and experience extremely slow vertical motions. E-W trending geomorphic features are indeed found in the southern part of western Puerto Rico as well as offshore and might have their origins in just this slow tectonic process. Examples are the Investigator Fault, Sierra Bermeja, Lajas

Valley, Monte Grande, and southern flank of Rio Guanijibo Valley. Other E-W features although probably to far north to be caused by these processes are the Cordillera Fault, and the western portion of La Cadena.

The focal mechanisms developed in the program indeed present a quandary. The near absence of low angle reverse faulting and the high number (50% of the total) of normal faulting suggest very complicated tectonics, perhaps induced by oblique subduction of a buoyant slab. Several normal faulting mechanisms spatially define a steep north-dipping plane, north side downthrown, and appear to be located within the downgoing plate. Projection of this fault, as a plane, reaches the surface near south side of Lajas Valley and the location of the S. Lajas Fault studied by Carol Prentice of the USGS (Prentice, 2003, Prentice and Mann, 2005). While it is too soon to draw a relationship between these two features, this is exactly the type of spatial relation between upper and locate plate deformation found in New Zealand.

The high angle reverse faults in combination with the normal faulting events might represent a complex internal deformation of the downgoing plate similar to the breaking of the North American plate as it descends beneath the northern margin of South America or the "escalator normal faulting" deformation of the Hikurangi Plateau observed beneath North Island New Zealand (Russo et al., 1992; Henrys et al., 2006).

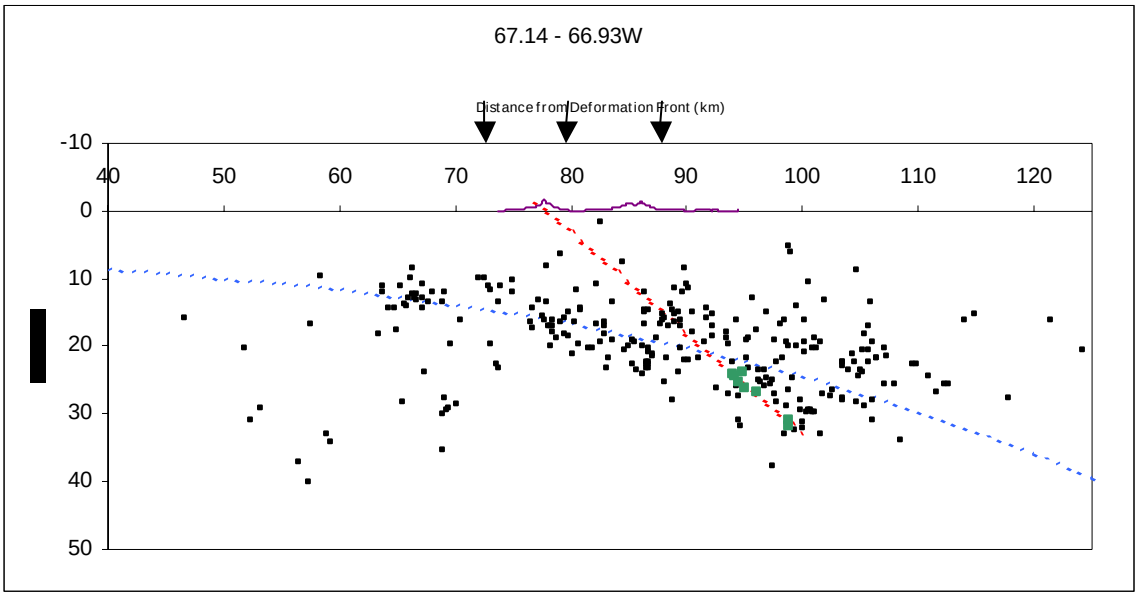

Figure 6. Vertical cross-section along western coast of Puerto Rico. Black symbols are DD locations. Blue dashed line is inferred location of Muertos Megathrust. Arrows show locations of, from left to right, S. coast of Puerto Rico, S. Lajas Fault, S. flank of Guanijibo river valley. Green symbols are events used to form 3 different focal mechanisms in western Puerto Rico. Each of these mechanisms (D, F, U) normal faults whose northerly dipping plane dips between 52 and 61º. Events forming these mechanisms lie on a northerly dipping plane dipping about 56º. Projection of this planar fault to the surface lays near the location of the S. Lajas Fault, a northerly dipping normal fault. If the fault in the downgoing Plate penetrates the upper plate, its upward continuation might be the S. Lajas Fault or a similar feature in western Puerto Rico.

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