PERGAMON

Journal of Geodynamics 33 (2002) 433–461

JOURNAL OF GEODYNAMICS

www.elsevier.com/locate/jgeodyn

The selectivity of the Ioannina VAN station

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Abstract

Two peculiar characteristics of the VAN method of short-term earthquake prediction are: (1) the existence of sensitive and insensitive sites to seismic electric signal (SES) and (2) the selective sensitivity of a sensitive station to SES from specific focal area(s). The process of their discovery, which so far has not been published adequately, is examined for the Ioannina (IOA) station. The sensitive site was discovered simply through repeatedly moving the temporary observation network. The selectivity map of the IOA station was made by first identifying the earthquake source areas with SESs which were considered to have been detected at IOA, and second by examining the direction of SESs from different such source areas. For the latter purpose, information from long dipoles appears to have been helpful. The selectivity map is empirically constructed and is updated regularly. We have independently tried to construct a selectivity map of IOA by examining VAN's raw SES records and by using the same criteria as VAN. The selectivity map we obtained was not exactly, but roughly similar to that of VAN. © 2002 Published by Elsevier Science Ltd.

1. Introduction

The VAN method of short-term earthquake prediction is based on the detection of the so-called seismic electric signal (SES) through continuously monitoring the geoelectric potential variations at sensitive sites (Varotsos and Alexopoulos, 1984a,b; Varotsos et al., 1996; Uyeda, 1996). SES is a transient change with typical magnitude of the order of 10^{-5} V/m. Its duration ranges from half a minute to several hours with varied waveforms, including bay type, rectangular type and comb shape. The VAN group claims that earthquakes with magnitude greater than ca. 5 in Ms(ATH) in Greece can be predicted with accuracy in epicenter of ca. 100 km and in magnitude [Ms(ATH)] of ca. 0.7. Ms(ATH) is the magnitude provided by the National Observatory of Athens. Despite its suffix s, it is not the surface wave magnitude but is empirically found to be related with the local magnitude ML by Ms(ATH) = ML + 0.5. The lead-time for the cases so far experienced has a range

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0264-3707/02/$ - see front matter
PII: S0264-3707(02)00006-6

from several hours (for some aftershocks) to about 2 weeks for isolated SES and from about 4 to 7 weeks for multiple SESs, which they call electrical activity. An isolated SES is a solitary signal, whereas many signals appear in a short time like 1 day in the case of electrical activity. When a SES-sensitive station happened to be close to the epicenter of an earthquake (EQ hereafter) with Ms(ATH) > ca. 6, another type of precursory variation lasting for several weeks, called the gradual variation of electric field (GVEF), is reported to have been observed though only rarely.

The VAN group claims that their predictions have been made possible by three major accomplishments: (1) establishment of techniques for signal/noise discrimination; (2) discoveries of source-station selectivity relations; (3) an inter-relationship among SES intensity E $(=\Delta V/L)$, epicentral distance (r) and EQ magnitude (M), i.e. $\log(E\times r) = a\mathrm{Ms(ATH)} + b$, where ΔV and L are the observed geopotential change on a dipole with length L, and a and b are empirical constants.

The selectivity relations are based on the observation that there exist sites that are sensitive to SESs from only specific EQ source areas. These areas may be quite far from recording site. The map showing the source areas which give SESs to a particular sensitive site is called the selectivity map of the site. The selectivity map is constructed empirically.

VAN's claims have met with a variety of reactions from the geoscientific community, including strong skepticism (see for instance some articles in Varotsos and Kulhanek, 1993; Geller, 1996; Lighthill, 1996). In view of the potential importance of the VAN method, a series of critical independent evaluations have been made; i.e. Nagao et al. (1996) on the noise rejection techniques; Uyeda and Al-Damegh (1999) on the general performance of the method and Uyeda et al. (1999) on the possible relationship between SES and earthquake source mechanism. The present paper is another of such efforts to scrutinize how the sensitive sites and selectivity relations have been found. The Ioannina (IOA) station has been the source of many of the VAN predictions, so we examined its selectivity map. For this purpose, VAN's original work-sheets and geoelectric data, kindly provided by Professor P. Varotsos, and the seismicity of the surrounding region have been cross-examined.

2. Discovery process of the Ioannina (IOA) station

Ioannina (39.6°N, 20.9°E) is VAN's fourth station, installed on 17 April, 1982, following Korinthos (March 1981), Glyfada (Athens, April 1981), Iraklion (Crete, December 1981) stations (Varotsos and Alexopoulos, 1984a). The main reasons for choosing Ioannina were, like in many other cases of VAN stations, (1) it was close to seismically active areas, (2) it was reasonably away from large cities or industrial areas, and (3) places for test sites were available in the Greek Army camps.

Once a general area is chosen, the strategy for site selection for long term observation was as follows: (1) electrically noisy sites were immediately abandoned after test recording of geopotential difference by a few short dipoles for a few days. The allowable noise level was of the order of 1×10^{-6} V/m. Clear recognition of variations due to geomagnetic changes against the background noise was also a practical criterion. (2) The site had to be judged sensitive to the precursory SES. For this, on-site test recording was run until some sizable EQs took place in reasonably close vicinity. If no SES was recognized, the measuring system was moved to another test site. The same process was repeated until some SES was believed to have been observed. VAN researchers knew from earlier experiences at other stations, notably their first station at Korinthos, that sensitivity to SES was highly site-dependent in both regional and local scales. Fig. 1a and b shows

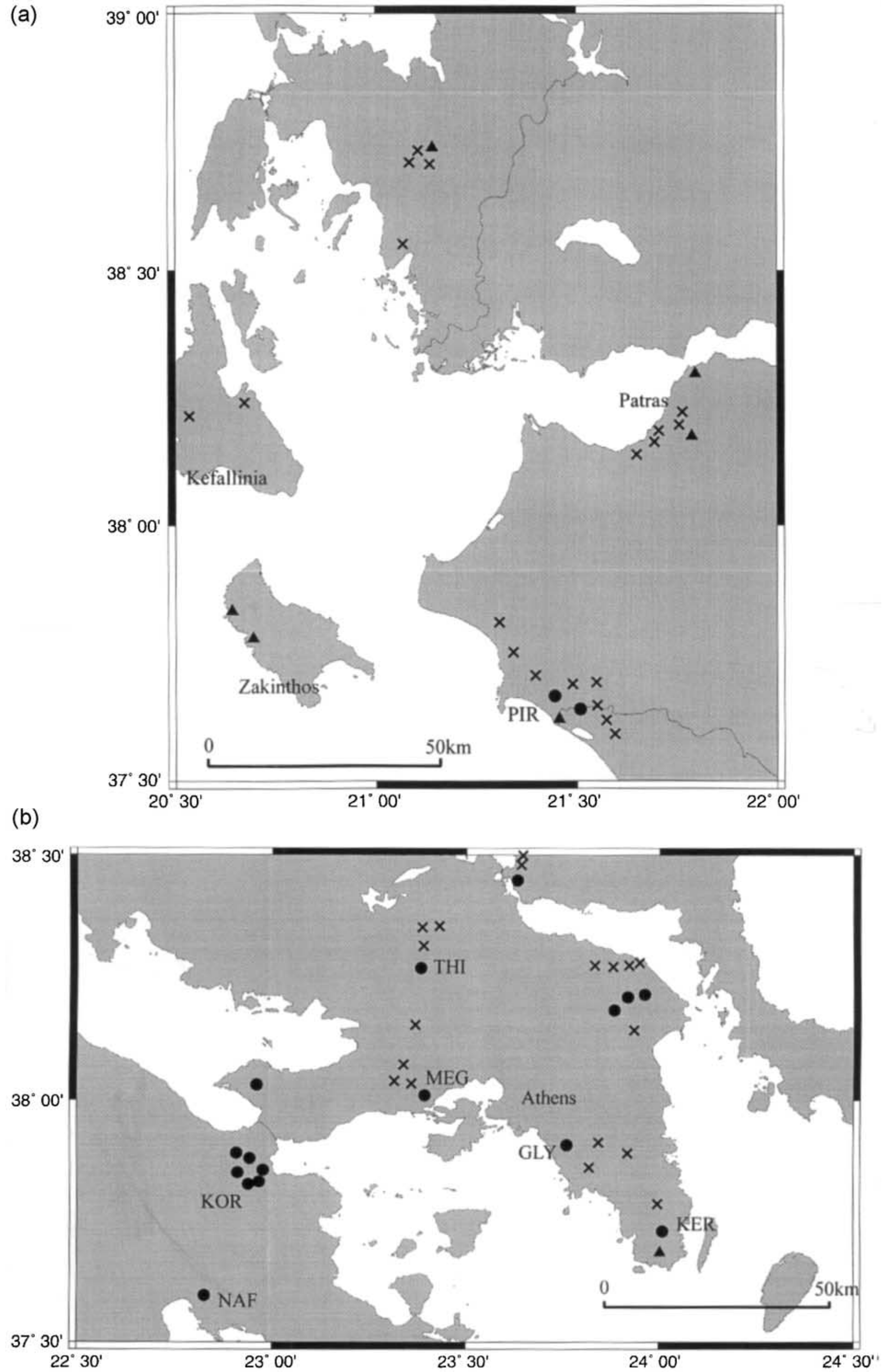

Fig. 1. Test sites for sensitive site finding in Greece (courtesy: P. Varotsos): (a) Western Greece, (b) Eastern Greece. Crosses: insensitive sites, circles and triangles: sensitive sites.

some examples of the sites of temporary stations, in the early days of the VAN method, set to find the sensitive sites.

What actually happened at Ioannina in 1982 was as follows: At each test site, one 50 m long short dipole was set in both NS and EW directions. Records were taken by a strip chart recorder with the sensitivity of ca. 1 mV/cm, and paper speed of 20 cm/h which was later reduced to 4–6 cm/h. Several places were tested for finding low noise sites. Among low noise sites, three were tested. The EQs in the surrounding area (39.0°–40.5°N, 19.5°–21.5°E) reported by the Preliminary Bulletin of Athens National Observatory were checked against the electric records.

The first site was run from 1 February to 11 March 1982 at 22 km north of the Ioannina Town (Fig. 2). EQs occurred on March 9 [Ms(ATH) = 4.7] and 11 March [Ms(ATH) = 4.6] to the west and northwest of the site as shown in Fig. 2. No indication of SES was recognized for these EQs, so that this site was judged to be insensitive. The second site was run from 11 March to 17 April at about 15 km SSW of the Ioannina Town. Again, no SES was recognized for EQ of 22 March [Ms(ATH) = 4.6), 2 EQs of 17 April (Ms(ATH) = 4.3] and other three smaller but closer EQs on 28 March, 10 April and 15 April, indicating this site was also insensitive. The third site was run from 18 April at 5 km north of the Ioannina Town. At this test site, SES-like signals were observed at about 11:03, 12:24 and 12:42 of 27 April (Fig. 3a). Then, an EQ [Ms(ATH) = 4.2]

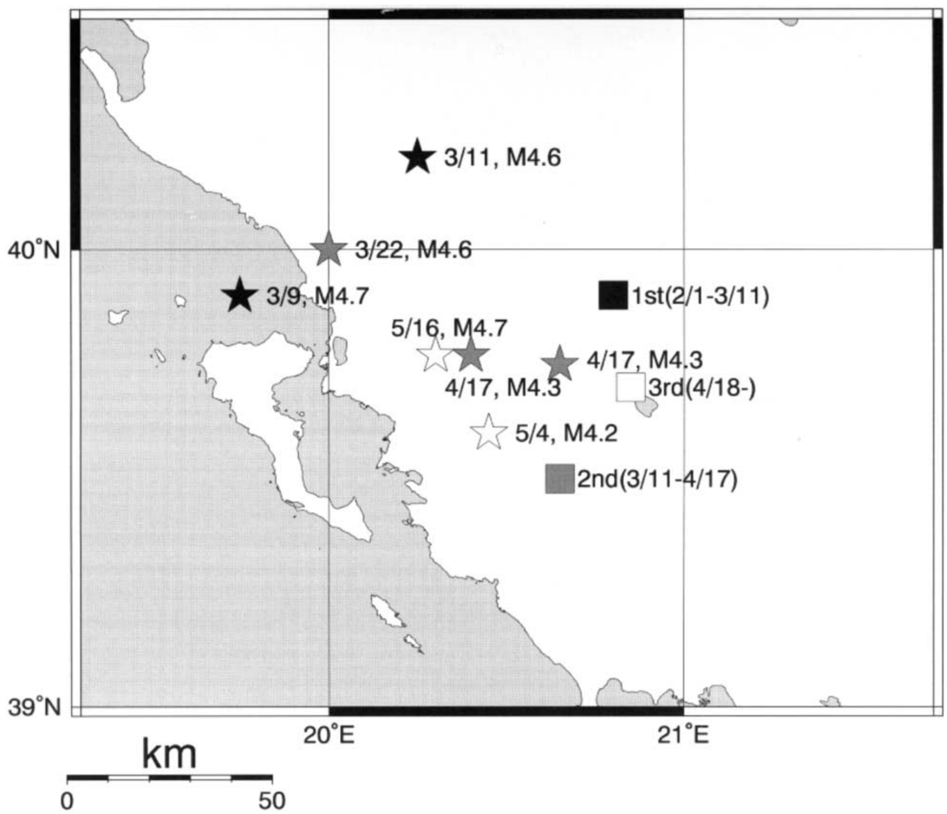

Fig. 2. Test sites in 1982 (squares with test duraion: month/day) and EQs [stars with date and Ms(ATH)] in Ioannina area (courtesy: P. Varotsos).

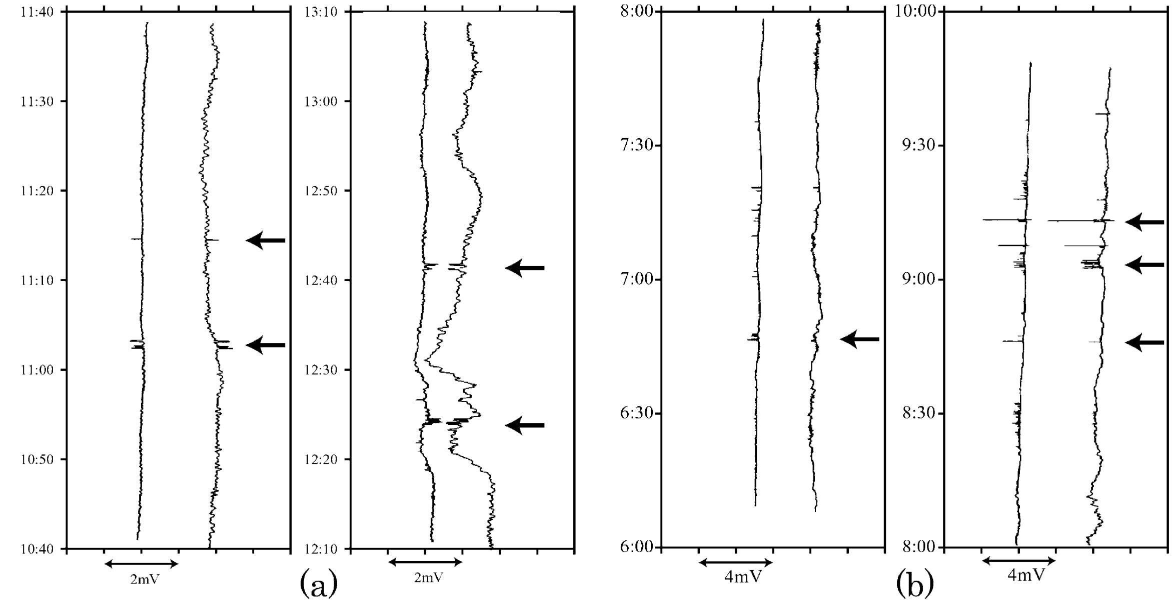

Fig. 3. Records of potential SES at Ioannina test site No. 3 (courtesy: P. Varotsos): (a) 27 April 1982, (b) 11 and 13 May 1982.

occurred to the west of the site on 4 May. Two more groups of SES-like signals (Fig. 3b) were observed at about 06:45 of 11 May and from 09:02 to 09:15 of 13 May and an EQ [Ms(ATH) = 4.7] occurred on 16 May again to the west. Suspect SESs mentioned above are included in Table 1 (Nos. 1–5). From these observations, this site was suspected to be sensitive. In order to ensure the repeatability of SES reception, the temporary site was run for about eight more months before installing permanent telemeter device.

3. Process of establishing the selectivity characteristics of the Ioannina station (1982–1984)

The layout of dipoles at the IOA station during 1982–1984 is shown in Fig. 4 left. There were dipoles $N^{100}S^{100}$, $N^{50}S^{50}$, W_1E_1 and W_2E_2. Both WE dipoles were 50 m long. Many more dipoles have been added later. Long dipoles at IOA, shown in Fig. 4 (right), started to operate in July 1985. These were introduced originally for the purpose of rejection of distant noise but later proved useful also for selectivity map construction. At present, there are 136 dipoles covering a wider area than that shown in Fig. 4 left (Varotsos et al., 1998). These numerous dipoles have been installed recently for the purpose of clarifying the spatial extent of the sensitive area.

Establishing the selectivity map of a station apparently is an empirical process. When suspect SESs first emerged, nothing was known about which seismic areas could have emitted them. We first tried to follow the process, which the VAN group possibly went through in the earliest years (April 1982–December 1984) through examining their original research notes. Left half of Table 1 is the exact copy of VAN's work sheets showing the total of 179 candidate SESs noted at the IOA station during this period. These candidate SESs were the geoelectric potential changes that

Table 1
Exact copy of VAN's Ioannina station work-sheets, in the earliest years before long dipoles were installed, on candidate SES (left half), and the EQs "reliably" correlated by VAN (Preliminary Bulletin of Athens National Observatory) and by the present authors (NEIC-PDE)

No.	Candidate SES						EQ								Telegram no.
	Date	Time (LT)	Duration (min)	Amplitude (10^{-6} V/m)		Remark	VAN group correlation				Our correlation				
				EW	NS		Date	Lat. N	Lon. E	Ms	Date	Lat. N	Lon. E	mb	
1	820427a	11:02	1	7.0	−6.0										
2	820427b	12:24	0.5	−6.0	8.0										
3	820427c	12:42	1	−7.0	6.0										
4	820511	6:46	2	??	−12.0										
5	820513	9:02	2	−40.0	−26.0										
6	820610	07:18	1	−26.0	−6.0										
7	820611	13:16	0.5	−16.0	0.0										
8	820722	18:18	20	0.0	−64.0										
9	820723a	02:20	25	0.0	−24.0										
10	820723b	04:26	4	0.0	−26.0										
11	820817	03:45	10	0.0	−40.0						EQ820822	39.6	20.4	4.5	
12	820921	16:22	1	0.0	−20.0										
13	820925a	00:53	15	−12.0	−10.0										
14	820925b	06:45	0.5	20.0	16.0										
15	820925c	06:52	1	−20.0	−16.0										
16	821010a	17:38	3	0.0	−10.0										
17	821010b	17:47	5	0.0	−12.0										
18	821015a	15:37	15	−32.0	10.0	May be questionable									
19	821015b	16:16	6	−20.0	−10.0	May be questionable									
20	821025	21:01	2	0.0	8.0	Oxi[a]									
21	821026	14:32	No recover	0.0	−30.0	Oxi									
22	821028	15:32	No recover	0.0	−8.0	Oxi									
23	821030	13:00	1.5	0.0	−10.0		EQ821031	39.4	21.4	3.7					
24	821031	15:30	23	0.0	6.2										
25	821102	12:13	1.5	0.0	−10.0										
26	821105	11:15	1.5	0.0	−10.0										
27	821107	0:56	1.5	0.0	−10.0										
28	821109	12:01	1.5	0.0	−10.0										
29	821110a	4:22	2.5	0.0	25.0		EQ821116	40.55	19.8	5.7	EQ821116	40.9	19.6	5.6	
30	821110b	7:37	2	0.0	15.0										
31	821110c	14:53	No recover	0.0	−24.0										
32	821111	13:43	No recover	0.0	12.0										
33	830101	14:00	1	0.0	10.0										

Table 1 (*continued*)

No.	Candidate SES						EQ								Telegram no.
	Date	Time (LT)	Duration (min)	Amplitude (10^{-6} V/m)		Remark	VAN group correlation				Our correlation				
				EW	NS		Date	Lat. N	Lon. E	Ms	Date	Lat. N	Lon. E	mb	
34	830106	12:38	∞	−16.0											
35	830112	22:37	Large	0.0	11.0										
36	830129a	10:10	0.5	0.0	−8.0										
37	830129b	17:48	Large	~−0?	−12.0	Magnetic?									
38	830203a	18:03	1	20.0	0.0										
39	830203b	19:00	> 30	24.0	8.0										
40	830204	9:28	30	20.0	10.0	Several similar signals, at least									
41	830208	21:07	7	0.0	−18.0		EQ830216	39.5	20.6	4.3					
42	830215	15:20		~74	~60	?May be a signal, but superimposed by									
43	830218	9:28	7	0.0	−20.0										
44	830223	13:30	> 60	−50.0	−35.0										
45	830225	9:56	40	0.0	−12.0		EQ830303	40.2	19.7	4.7					56
46	830226a	1:13	40–50	0.0	−12.0	?	EQ830303	40.2	19.7	4.7					56
47	830226b	5:50	70	0.0	30.0	?									
48	830227	16:50	80	0.0	−30.0	NOT in AMF[b]	EQ830303	40.2	19.7	4.7	EQ830303	40.2	19.6	4.4	56
49	830228	7:13	~10	−24.0	−11.0										
50	830303	7:50	3	0.0	15.0										
51	830304	10:03	> 100	32.0	28.0	?									
52	830305	7:46	??	17.6	22.6										
53	830307a	6:15	20	0.0	−6.2										
54	830307b	19:23	15	0.0	−7.6										
55	830310	7:17	7	0.0	−20.0						EQ830317	38.5	21.5	4.2	
56	830317	7:30	13	0.0	−16.2	Good									
57	830320	23:03	4	18.0											
58	830322a	1:55	4	15.0											
59	830322b	10:31	4	13.0											
60	830322c	17:27	5	17.6											
61	830322d	23:15	4	13.0											
62	830323a	5:04	4	13.0											
63	830323b	11:14	3	13.0											
64	830323c	11:50	??	0.0	−15.0	Good									
65	830323d	17:35	12	13.0	0.0	Good?									

(*continued on next page*)

Table 1 (*continued*)

No.	Candidate SES						EQ								Telegram no.
	Date	Time (LT)	Duration (min)	Amplitude (10^{-6} V/m)		Remark	VAN group correlation				Our correlation				
				EW	NS		Date	Lat. N	Lon. E	Ms	Date	Lat. N	Lon. E	mb	
66	830324	7:08	??	0.0	−7.6	Good									
67	830327	13:11	0.5∼1	0.0	10.0	Smooth									
68	830330	6:37	8	0.0	−16.2	Good									
69	830401	5:20	Large	0.0	−8.0										
70	830403	13:13	1.5	0.0	−11.2	Unusual									
71	830414	14:54	1.5	0.0	42.0										
72	830419	9:40	3	0.0	−8.0	Suspicious very									
73	830421	10:50	20	0.0	−6.0	Small									
74	830423	7:28	10	76.0	−38.0	Suspicious									
75	830514	7:03	6	−45.0	0.0	Suspicious									
76	830522a	9:07	??	20.0	0.0	Suspicious	EQ830524??	37.8	20.7	4.7					
77	830622b	12:32		0.0	−18.8	Suspicious									
78	830622c	13:33	2	0.0	−18.8	Suspicious									
79	830625	15:23	7	0.0	−15.0										
80	830628	15:36	5+1	0.0	−13.8										
81	830703	9:01	∼1	0.0	−18.8										
82	830706	18:24	7	0.0	−15.0	Double?									
83	830709	16:53	8	0.0	−13.8	Suspicious									
84	830711	13:50	2	0.0	15.0										
85	830712	7:50	45	−15.2	−7.6	Suspicious continuous									
86	830714	6:43	1+1	0.0	16.2										
87	830723	12:45	4	0.0	−21.2										
88	830726	17:04	4.5	0.0	−17.6										
89	830730a	15:21	2.5	0.0	−12.6										
90	830730b	15:57	0.5	0.0	−15.0										
91	830802a	11:52	5.5	0.0	−13.8										
92	830802b	16:16	2	0.0	7.6										
93	830804	18:44	5.5	0.0	−12.6										
94	830806	19:33	3	0.0	−12.6										
95	830810	15:19	5.5	0.0	−12.6										
96	830820	12:17	4	0.0	−16.2										
97	830824	14:44	4	0.0	−15.0										
98	830827	12:58	3.5	0.0	−16.2						EQ830902	37.6	20.7	4.9	
99	830830a	9:20	Uncount	0.0	−17.6										
100	830830b	11:22	3	0.0	−15.0	cf. Pirgos					EQ830902	37.6	20.7	4.9	

Table 1 (*continued*)

No.	Candidate SES						EQ								Telegram no.
	Date	Time (LT)	Duration (min)	Amplitude (10^{-6} V/m)		Remark	VAN group correlation				Our correlation				
				EW	NS		Date	Lat. N	Lon. E	Ms	Date	Lat. N	Lon. E	mb	
101	830901	12:12	2	0.0	−11.2	Good	EQ830905A	41.4	20.6	4.8					
102	830903	9:09	3.5	0.0	−11.2	Good	EQ830905B	41.5	20.8	4.6					
							EQ830905C	41.4	21.0	4.7					
103	830904a	15:00	∞	0.0	−20.0										
104	830904b	16:10	25	0.0	−15.0										
105	830904c	20:16	∞	0.0	−37.6										
106	830905	14:50	15	0.0	−10.0										
107	830906a	11:12	1	0.0	−17.6	Good	EQ830910	42.3	21.0	5.3	EQ830909A	37.5	20.9	5.1	
108	830906b	14:32	1	0.0	−18.8	Good	EQ830910	42.3	21.0	5.3	EQ830909B	37.55	20.8	4.7	
109	830909a	10:55	1	0.0	−17.6	Good	EQ830910	42.3	21.0	5.3	EQ930911	38.8	22.4	4.2	
110	830909b	11:12	2	0.0	−16.2	Good	EQ830910	42.3	21.0	5.3	EQ930911	38.8	22.4	4.2	
111	830913a	2:03	7	0.0	−10.0	Good					EQ930919A	38.73	22.42	4.5	
112	830913b	8:35	55	0.0	−20.8	New form					EQ930919B	38.75	22.37	4.5	
113	830913c	11:31	1	0.0	−12.6	?									
114	830913d	17:31	15	0.0	−17.6	Rather suspicious									
115	830914a	14:47	10	0.0	−17.6						EQ930919A	38.73	22.42	4.5	
116	830914b	15:26	4	0.0	−21.2						EQ930919B	38.75	22.37	4.5	
117	830914c	17:56	3	0.0	−41.2	No									
118	830915	11:14	1	0.0	−15.0										
119	830917	16:50	4	0.0	−11.2										
120	830919a	6:52	14	0.0	−17.6	?									
121	830919b	8:18	11	0.0	−15.0										
122	830927	17:17	4	−9.0	−8.8										
123	831005	18:56	2	80.0	35.0	cf. Pirgos signals									
124	831006	13:18	2.5	56.0	25.0	Strange									
125	831009a	6:58	0.5	0.0	−12.6										
126	831009b	7:02	0.5	0.0	−12.6										
127	831009c	7:12	0.5	0.0	−12.6										
128	831009d	7:16	0.5	0.0	−12.6										
129	831009e	8:06	2	0.0	7.6										
130	831009f	8:13	4	0.0	15.0	Good									
131	831013	13:03	5	0.0	−15.0	Good									
132	831016a	12:19	1–2	0.0	−22.6										
133	831016b	12:25	1–2	0.0	−20.0										

(*continued on next page*)

Table 1 (*continued*)

No.	Candidate SES						EQ								Telegram no.
	Date	Time (LT)	Duration (min)	Amplitude (10^{-6} V/m)		Remark	VAN group correlation				Our correlation				
				EW	NS		Date	Lat. N	Lon. E	Ms	Date	Lat. N	Lon. E	mb	
134	831016c	12:35	2	0.0	−20.0										
135	831020a	7:16	1	0.0	−12.6										
136	831020b	10:33	1.5	0.0	8.8										
137	831024	7:40	0.5	0.0	−10.0										
138	831025	5:05	8	0.0	−10.0										
139	831031a	18:45	1	10.0	15.0	Strange									
140	831031b	20:09	25	10.0	15.0	?									
141	831101	4:06		−22.0	−28.0	?									
142	831106	1:00		−15.0	0.0	Signal does not recover									
143	831123a	10:30	1	0.0	10.0										
144	831123b	10:30	1	0.0	12.6										
145	831123c	10:30	1	0.0	15.0										
146	831126	13:00	1	0.0	−23.0	??									
147	831216	17:12	1	20.0	0.0	Strange									
148	831222a	1:33	1	0.0	14.0		EQ831225	41.5	18.8	5.0	EQ831225	42.0	19.1	5.3	
149	831222b	1:46	5	0.0	15.6		EQ831225	41.5	18.8	5.0	EQ831225	42.0	19.1	5.3	
150	831223	9:30	1	0.0	−9.0										
151	831225	6:45	0.5	0.0	24.0						EQ831228	40.9	20.9	4.2	
152	840103	5:37	45	37.6	0.0		EQ840107	39.9	20.4	4.5					
153	840105	19:17	5	0.0	−10.0										
154	840108a	19:25	1	0.0	17.0		EQ840113	41.6	18.7	5.1	EQ840114	40.1	19.7	4.1	
155	840108b	19:55	5	0.0	17.6		EQ840113	41.6	18.7	5.1	EQ840114	40.1	19.7	4.1	
156	840108c	20:10	2.5	0.0	17.6		EQ840113	41.6	18.7	5.1	EQ840114	40.1	19.7	4.1	
157	840208	12:45	70	55.0	0.0		EQ840209??	40.6	21.6	4.8	EQ840209	40.5	21.6	4.3	199
158	840209	1:37	Difficult > 25	−57.6	Not working										
159	840210	14:09	2	0.0	25.0						EQ840211	38.4	22.1	5.3	
160	840223	4:15	1	0.0	15.6						EQ840225	38.4	21.7	4.8	
161	840226	11:12	0.5	0.0	18.8						EQ840229	38.4	21.7	4.4	
162	840228	19:21	0.5	0.0	13.8										
163	840229	8:29	3	−13.8	−4.4										
164	840327	19:09	3.5	0.0	26.0		EQ840330	41.2	20.0	4.8					241
165	841331	14:23	1	0.0	8.8										
166	840401	5:19	1	0.0	17.6										
167	840411a	9:25	3 + 0.5 + 1	0.0	−9.6										
168	840411b	17:10	1	0.0	15.0										

Table 1 (*continued*)

No.	Candidate SES						EQ								Telegram no.
	Date	Time (LT)	Duration (min)	Amplitude (10^{-6} V/m)		Remark	VAN group correlation				Our correlation				
				EW	NS		Date	Lat. N	Lon. E	Ms	Date	Lat. N	Lon. E	mb	
169	840501	21:50	22	0.0	18.8		EQ840505	39.1	21.9	3.6					
170	840503	21:13	> 30 min	0.0	−10.0										
171	840506	6:51	1.5	0.0	13.8										
172	840513	8:28	~0.75	0.0	13.8										
173	840520a	5:47	−0.75	0.0	10.0										
174	840520b	7:57	Large	21.6	0.0										
175	840531a	10:08	1	−20.0	0.0		EQ840601	37.6	20.7	5.1	EQ840601	37.7	21.0	4.6	
176	840531b	11:05	1	−11.0	0.0										
177	840913	14:44	5		–										
178	841112	4:25	7		+										
179	841210	2:15	Large	+	+										

[a] Oxi means no in Greek.

[b] AMF is a station name.

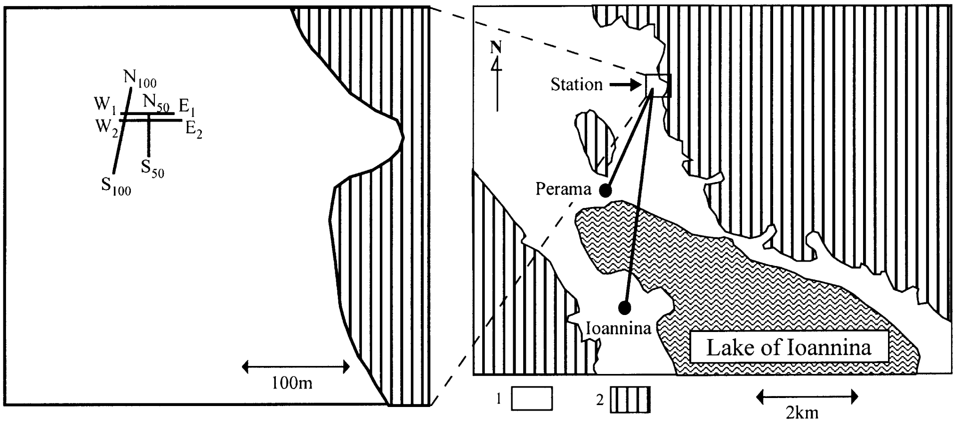

Fig. 4. Dipole configuration at IOA (arranged from Varotsos et al., 1996). Left: short dipoles during 1982–1984. Right: long dipoles installed in 1985. (1) Quaternary deposits; (2) Alpine formation.

survived the preliminary noise rejection process, i.e. removal of such obvious noise as magneto-telluric and electrode instability origin. Naturally, most of these candidate SESs were not real SES as will be elaborated below.

As candidate SESs were recognized, the VAN group tried to correlate them with EQs that occurred subsequently. This was a post factum operation. The EQ data source available for their day-to-day operation was the Preliminary Bulletin of Athens National Observatory, namely the Ten Days Preliminary Seismogram Readings at Athens. The Final Catalog, also issued by the National Observatory of Athens, was available for their later use.

Judging from their work-sheets, it appears that their main guiding rules for SES–EQ correlation were:

1. SES was to be correlated with EQ that followed the SES within a reasonable time. This delay time was not known a priori.
2. When there were more than one candidate EQs for one SES, EQ with large magnitude and close epicenter was adopted. Conversely, when there were more than one suspect SESs preceding one EQ, the signal with greatest amplitude was adopted as the best candidate SES.

Apparently there was no definite physical model for these guidelines. They were a set of assumptions of experiment based on a reasonable physical guess. Thus, there was considerable room for subjective judgement. As will be shown later, only correspondences where both SES and EQ were reasonably isolated were regarded reliable.

The first changes recognized as candidate SESs, after identifying IOA as a sensitive station, were Nos. 6 and 7 in Table 1. Inspection of the records (Fig. 5) suggested that the change No. 6 (820610) could be the more plausible candidate because it was stronger and appeared in both NS and EW directions. (In the following, notation xxyyzz means yr, month, day.)

Given the Preliminary Bulletin data, EQ820703 could have been correlated to the candidate SES. But according to the Final Catalog, the same EQ was located at almost 100 km SE and its Ms(ATH) was only 3.7. Then, the correlation of the change No. 6 (820610) and EQ820703 required an epicentral distance $\sim$100 km for Ms(ATH) 3.7 EQ with lead time Δt $\sim$23 days. This correlation was considered unconvincing (Table 2a).

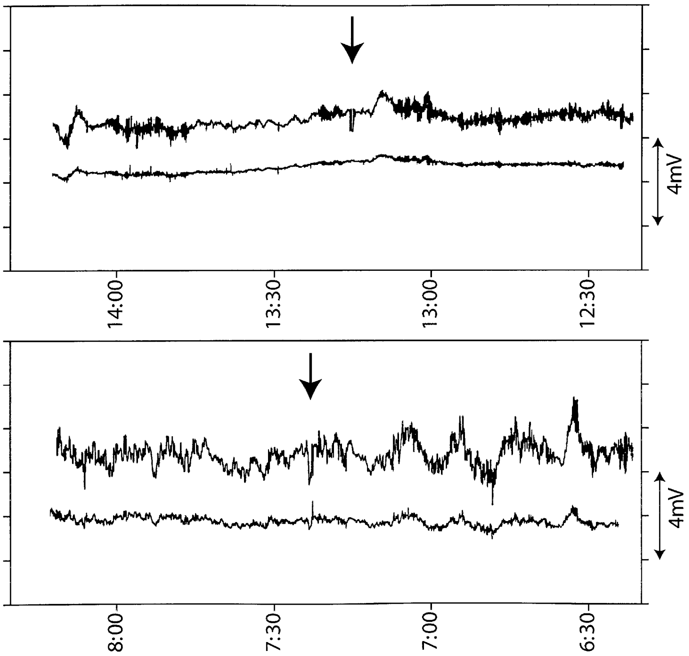

Fig. 5. Records of the changes 820610 (lower panel No. 6 in Table 1) and 820611 (upper panel No. 7) (courtesy: P. Varotsos). Candidate SESs are marked by arrows. In Figs 5, 6 and 7, upper record is EW dipole and lower record is NS dipole.

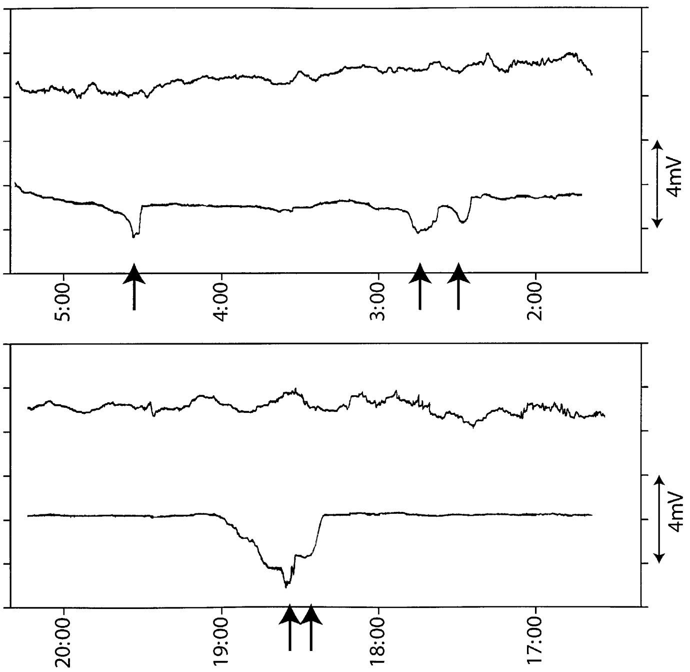

Fig. 6. Records of the changes 820722 (lower panel No. 8), 820723a (upper panel No. 9), 820723b (No. 10) (courtesy: P. Varotsos).

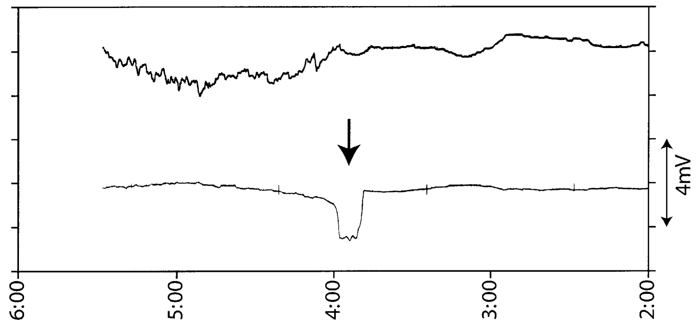

Fig. 7. Record of the change 820817 (No. 11) (courtesy: P. Varotsos).

Table 2
VAN's first candidate SESs and subsequent earthquakes

	EQ	Ms(ATH)	Eipcenter relative to IOA
a. EQs which followed the change No. 6 in Table 1			
Preliminary bulletin	EQ820703	4.3	20 km E
Final catalogue	EQ820613	No M	No epicenter
	EQ820614	No M	No epicenter
	EQ820703	3.7	100 km SE
	EQ820720	No M	80 km SSW
	EQ820721	No M	80 km SSE
b. EQs which followed the changes Nos. 8–10 in Table 1			
Preliminary bulletin	EQ820727	4.9	80 km SSW
	EQ820804a	5.4	50 km WNW
	EQ820804b	4.7	30 km W
	EQ820805	4.3	15 km SW
	EQ820807	4.4	20 km W
Final catalogue	EQ820727	4.9	100 km WNW
	EQ820804a	5.3	40 km WNW
	EQ820804b	4.5	40 km W
	EQ820805	4.2	15 km SSE
	EQ820807	4.3	20 km NNW
	EQ820807	No M	50 km W
	EQ820811	No M	20 km WSW
	EQ820812a	No M	40 km NW
	EQ820812b	No M	50 km W
	EQ820813	No M	50 km W
c. EQs which followed the change No. 11 in Table 1			
Preliminary bulletin	EQ820822a	4.6	80 km W
	EQ820822b	4.7	45 km SW
Final catalogue	EQ820822a	4.5	60 km WSW
	EQ820822b	4.4	45 km SW
	EQ820823	No M	40 km W
	EQ820829	4.5	40 km W

The next series of possible SESs were Nos. 8 ~ 10 in Table 1 and Fig. 6. The EQs that followed these three changes are listed in Table 2b. Since there were three Ms(ATH) > 4.5 EQs, they could have been correlated with each other. However, which change corresponded to which EQ was hard to determine.

The next suspect SES was No. 11 (820817) and the EQs that followed it were as listed in Table 2c. The change No. 11 was a distinct one (Fig. 7). The Final Catalogue gave the

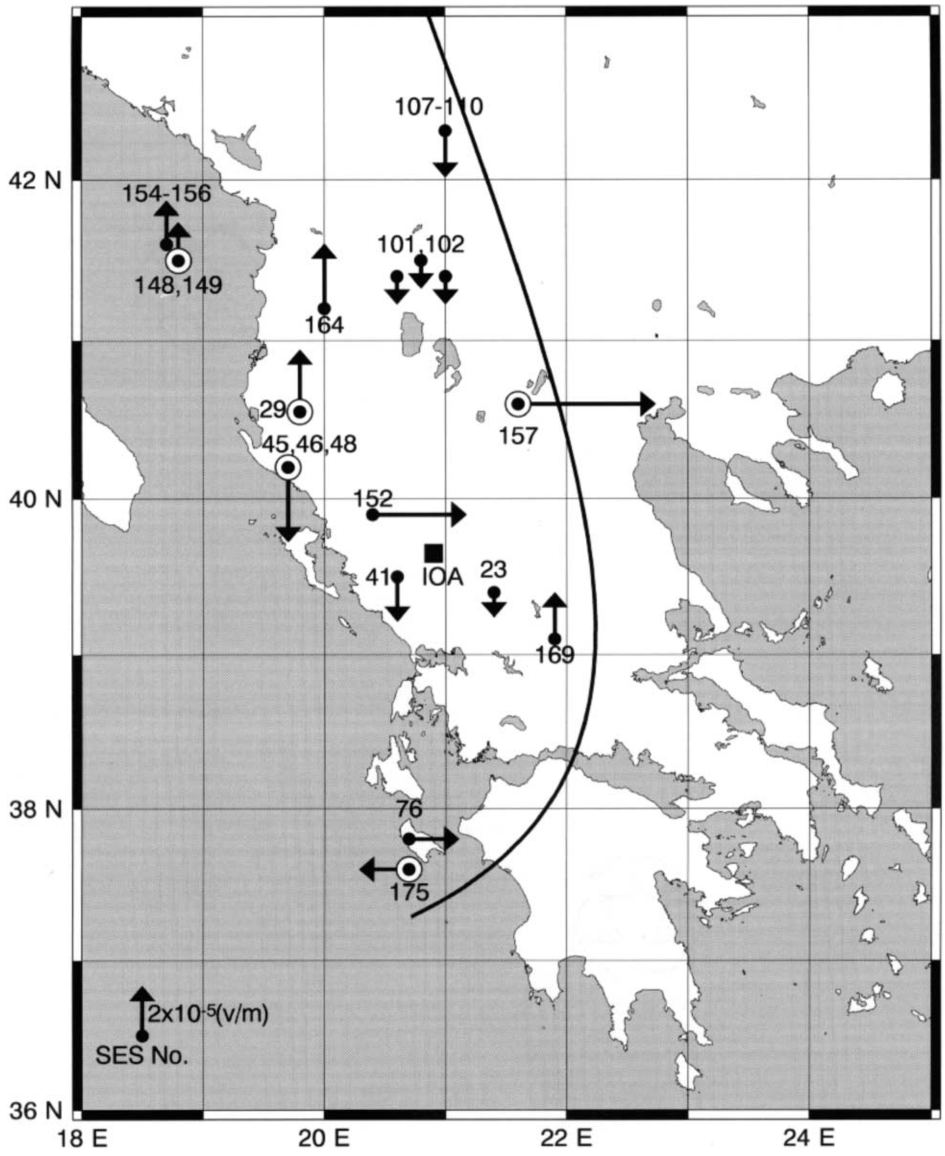

Fig. 8. Reliable SES–EQ correlations and the selectivity map of IOA as of 1984 according to VAN. Numbers correspond to those in Table 1. Five cases, which agreed with our correlations, are marked by double circles. Arrows indicate short dipole SES.

occurrences of three EQs with comparable Ms(ATH) in the westerly direction, i.e. EQ820822a, EQ820822b and EQ820829. Again, one to one correspondence was hard to identify.

After having made similar trial correlation on each suspect SES, the VAN group considered 14 correlations reliable as listed in the column "VAN group correlation" of Table 1 and illustrated in Fig. 8, which actually was the selectivity map of the IOA station as of late 1984. It should be noted that even in their reliable correlations, some correspondence was not unique, e.g., EQ830303 with SES830225, SES830226a and SES830227: EQ830905A,B.C with SES830901 and SES830903: EQ830910 with SES830906a,b and SES830909a,b: EQ831225 with SES 831222a,b: EQ840113 with SES840108a,b,c. They are counted as one correlation. Three small EQs (EQ821031, EQ830216 and EQ840505) were correlated because of their proximity to IOA.

In order to infer the VAN's methodology of selecting reliable correlations, we tried to examine what an isolated EQ actually meant to them by the following analysis. In each case of their reliable correlation, we plotted EQs that occurred within 8 days after the concerned SES in an epicentral distance–magnitude diagram (Fig. 9). Eight days was chosen simply because it was the longest lead-time in their reliable correlations. In each case, EQs are plotted in time sequence as connected by thin lines starting from the first EQ after the SES marked S. The EQs adopted by the VAN group are shown by black triangles. As expected, the selected earthquakes are indeed isolated in the sense that they stand out in terms of either large magnitude or small epicentral distance. Three prediction telegrams were dispatched among themselves for the cases of EQ830303, EQ840209 and EQ840330. The contents of the two telegrams, available to us, were vague: i.e. Telegram #199 reads "SES on 830208 indicates EQ with M4.3 near IOA or M5.3 at 70 km distance from IOA" and #241 reads "SES on 840327 indicates EQ ranging from M4.3 near IOA to M.5.3 in Albania". These contents shown as "prediction" in Fig. 9 (No. 157 EQ840209 and No. 164 EQ840330) are rather reasonable. Telegram numbers indicate that they were practicing many internal trial predictions at that stage, mostly based on data from other stations.

We, then, combined these diagrams (Fig. 10). As in Fig. 9, black and open triangles are the chosen and unchosen EQs. It is remarkable that one can delineate the areas C and U so that the chosen EQs were almost exclusively in the region C and the area U is populated only by the uncorrelated EQs. The same line is drawn in each diagram in Fig. 9 for reference. There are some unchosen EQs in the region C, but most of them were superseded by more isolated ones that occurred in the same eight days as connected by arrows. Two open triangles in high magnitude area correspond to the cases of EQ830910 and EQ840209 (see Fig. 9). Their epicenters were in the southern direction viewed from IOA in contrast to other EQs in the same 8 days. This could have been the reason for their rejection probably based on experience.

We have independently tried to identify possible correlations through checking the whole list of candidate SESs (Table 1) and EQs. After 32 changes with notes expressing VAN's doubts on the validity, such as oxi (no in English), suspicious and so on, were discarded, there remained 147 candidate SESs in Table 1. For EQ information, we used the NEIC-PDE catalog, instead of the Athens Preliminary Bulletin, for its wider availability, which would help checking by other scientists. Only EQs with mb (PDE) $\geqslant$4.0 [practically Ms(ATH)$\geqslant$4.3 (Hamada, 1993)] were considered as candidate EQs. As shown in Fig. 11, there were 384 such EQs in the region during the study period (1982/4/17–1984/12/31), but 182 of them occurred in the Kefallinia Island region (see Fig. 1a for the location).

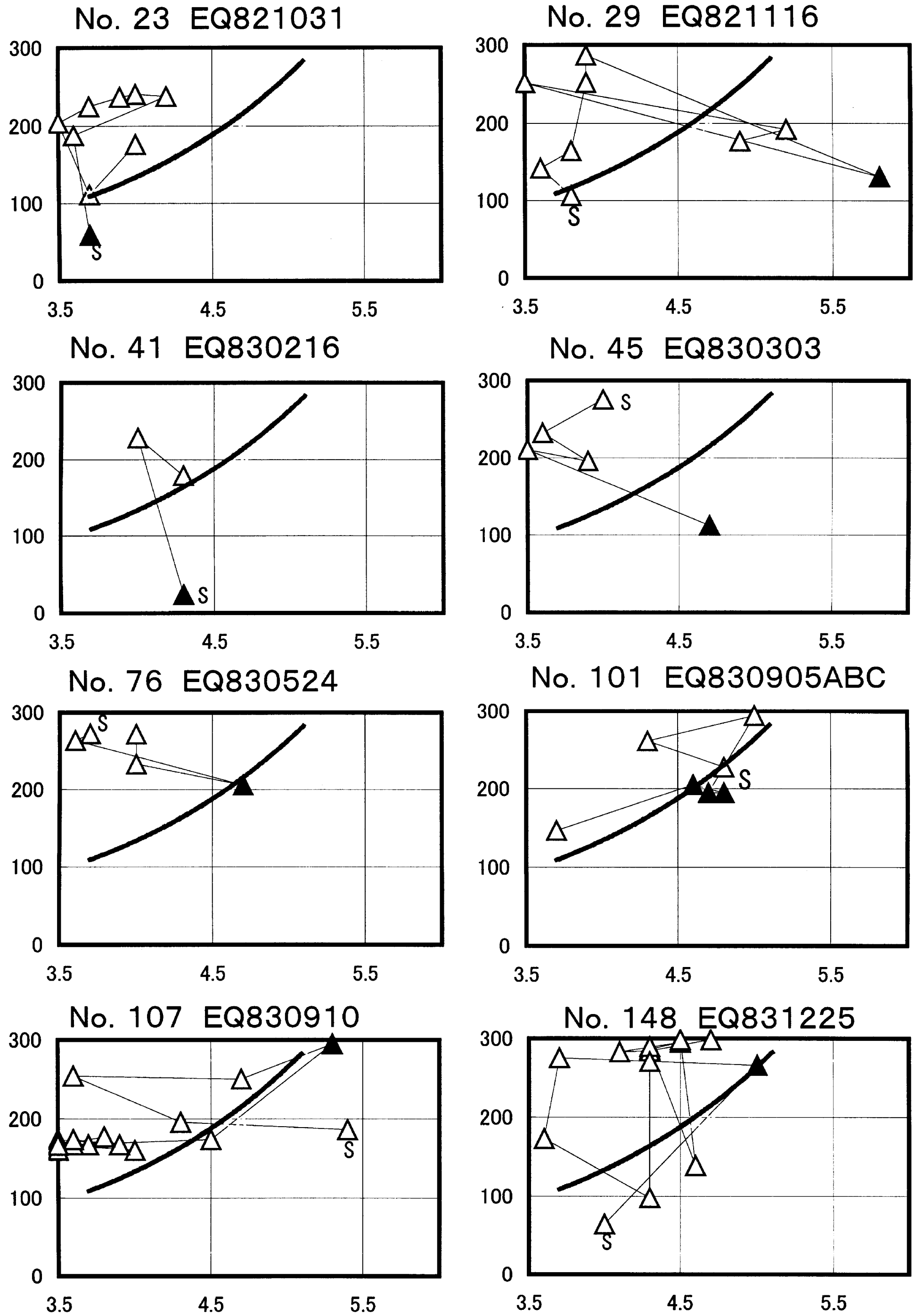

Fig. 9. Epicentral distance–magnitude diagrams (after Athens PB) for EQs that occurred in 8 days after the SES. The time sequences of EQs (triangles) are shown by thin lines starting with the first one marked S. Black triangles are the correlated EQs. For the thick line, see Fig. 10. Prediction telegrams were dispatched for the cases of EQ840209 and EQ840330 as indicated by "prediction". Vertical axis in km; horizontal axis in Ms(ATH).

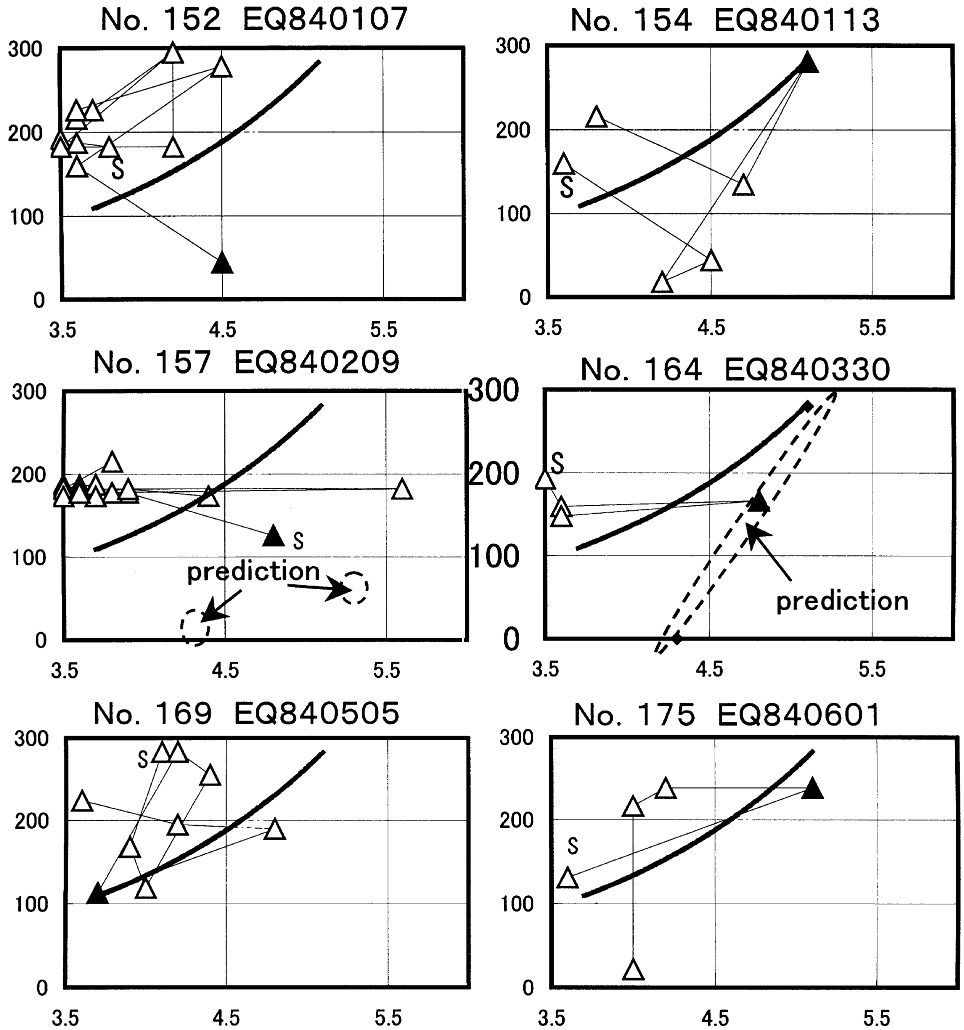

Fig. 9. *continued.*

We first deal with these EQs in the Kefallinia Island region. Out of the 182 EQs, 131 belonged to two swarm activities in January–April 1983. All except one of 11 mb$\geqslant$5 EQs in the Kefallinia Island region during the study period occurred in these swarms. We first checked if there were candidate SESs within eight days before each of these 11 mb$\geqslant$5 EQs. For the six mb$\geqslant$5 EQs of the first swarm starting with EQ830117(mb 6.1), there were only three candidate SESs (830101,830106,830112). For the four mb$\geqslant$5 EQs of the second swarm starting with EQ830323(mb 5.8), there were 11 candidate SESs (830310$\sim$830324). One to one correspondence in these cases was impossible. They do not fit the VAN's definition of reliable correlation between isolated SES and EQ. Actually, "VAN group correlation" in Table 1 does not contain them. It is important to note here that these EQs in the the Kefallinia Island region were actually predicted

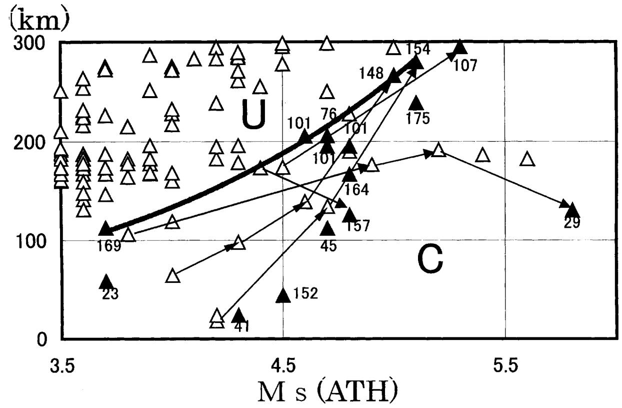

Fig. 10. Combined epicentral distance–magnitude diagrams. Vertical axis in km; horizontal axis in Ms(ATH). The thick line defines the areas C and U so that the chosen EQs were almost exclusively in the area C and the area U is populated only by uncorrelated EQs. The same line is drawn in each diagram in Fig. 9 for reference.

by the VAN group on the basis of SESs at their Pirgos (PIR) station (Varotsos and Alexopoulos, 1984a,b), indicating that the region was in the selectivity map of PIR station (see Fig. 1a for location of PIR) at that time. We say "at that time" because, as shown by Uyeda et al. (1999), the Kefallinia Island region became part of the IOA selectivity map area after 1988, coinciding with the time when the source mechanism of EQs in that region shifted from strike-slip type to thrust type. Considering these, we judged that the Kefallinia Island region was out of IOA selectivity map and eliminated the EQs in that region (182 in number) from candidate EQs.

We then plotted the remaining 202 EQs on an epicentral distance–magnitude diagram and found that 137 of them were placed in the area C. We assume that Figs. 9 and 10 indicated that only EQs in the area C could have generated observable SES at IOA. Candidate SESs within 8 days were found for 67 of 137. Of these, 14 reliable correlations were found to have both EQs and SESs sufficiently isolated in time to permit a unique match (Table 1 and Fig. 12). Fig. 13 shows the set of our version of epicentral distance–magnitude diagrams for the selected 14 "reliable" correlations (19 EQs) and Fig. 14 is their combined presentation.

Only five cases are common to VAN's reliable correlations and our reliable correlations. They are related with Nos. 29, 48, 148, 157, and 175 in Table 1. Thus, from about 180 candidate short dipole SESs and about 200 candidate EQs, both the VAN group and we independently picked up 14 cases as reliable correlations, and five of them coincided. The reasons for the differences between the two correlations are; (a) the VAN adopted three $mb < 4$ EQs and (b) the two catalogs (Athens Final catalog and NEIC-PDE catalog) often gave different magnitude values and epicenters for the same EQs. We do not claim that our correlations are any better than VAN's, but the discrepancy seems to witness that reliable prediction was difficult to make at the early stage of the research. If the common correlations were really meaningful ones, five out of 175 short dipole candidate SESs, namely about 5% could be taken as real SESs. This percentage is higher compared with the 0.5–2.0% range which we obtained through our independent check of VAN's full criteria for noise rejection on their later data (Nagao et al., 1996).

It may be observed in Figs. 8, 11 and 12 that there are areas, such as Kefallinia region, eastern Greece and the Aegean Sea, where significant EQs occurred but reliably correlatable SESs have not been identified at IOA. These areas are considered as IOA's non-selectivity areas. It was later noticed that the IOA selectivity map area was parallel with the NNW-SSE general geotectonic trend of the western Greece (e.g. Papanikolaou, 1993).

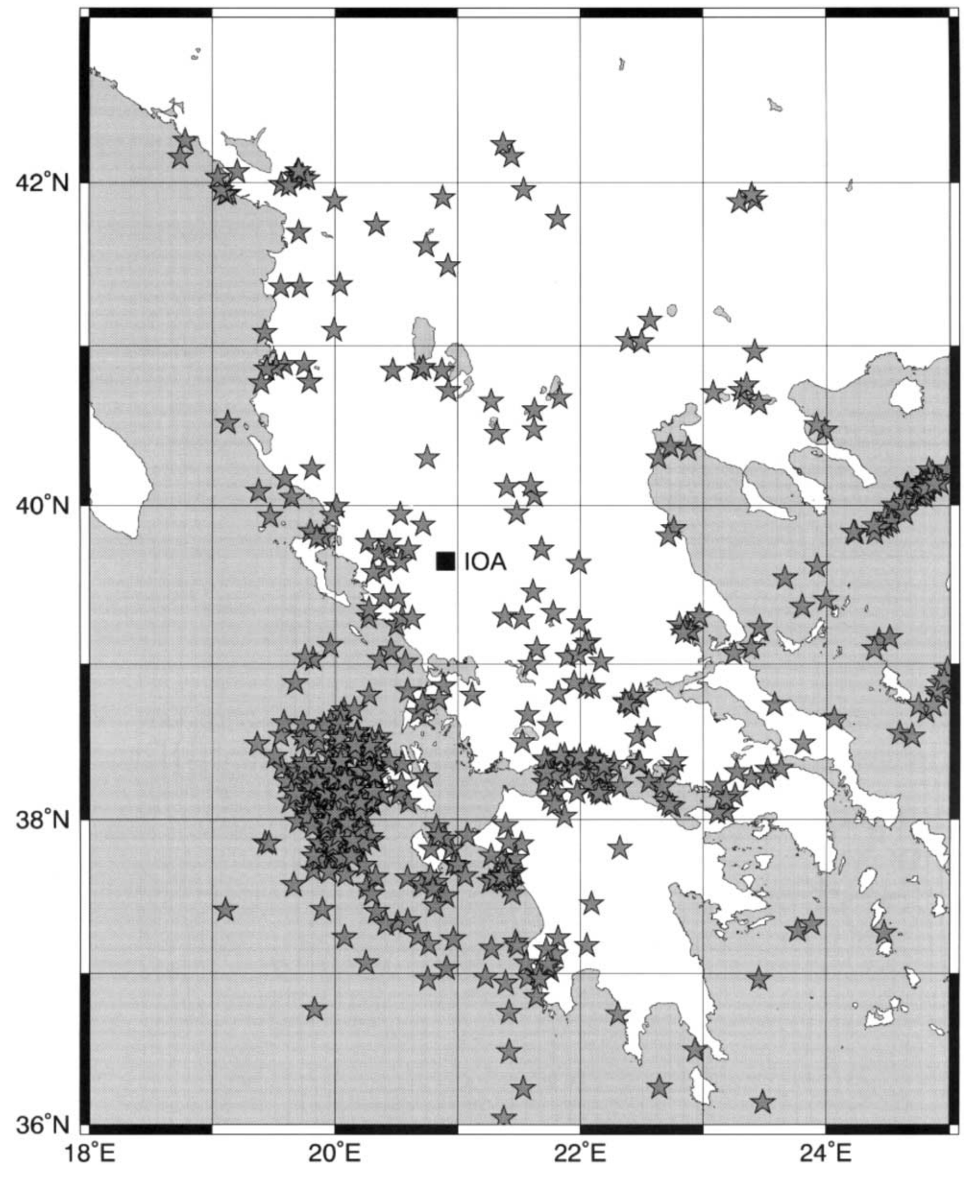

Fig. 11. All *mb* (PDE) ⩾ 4.0 EQs for 17 April 1982–31 December 1984.

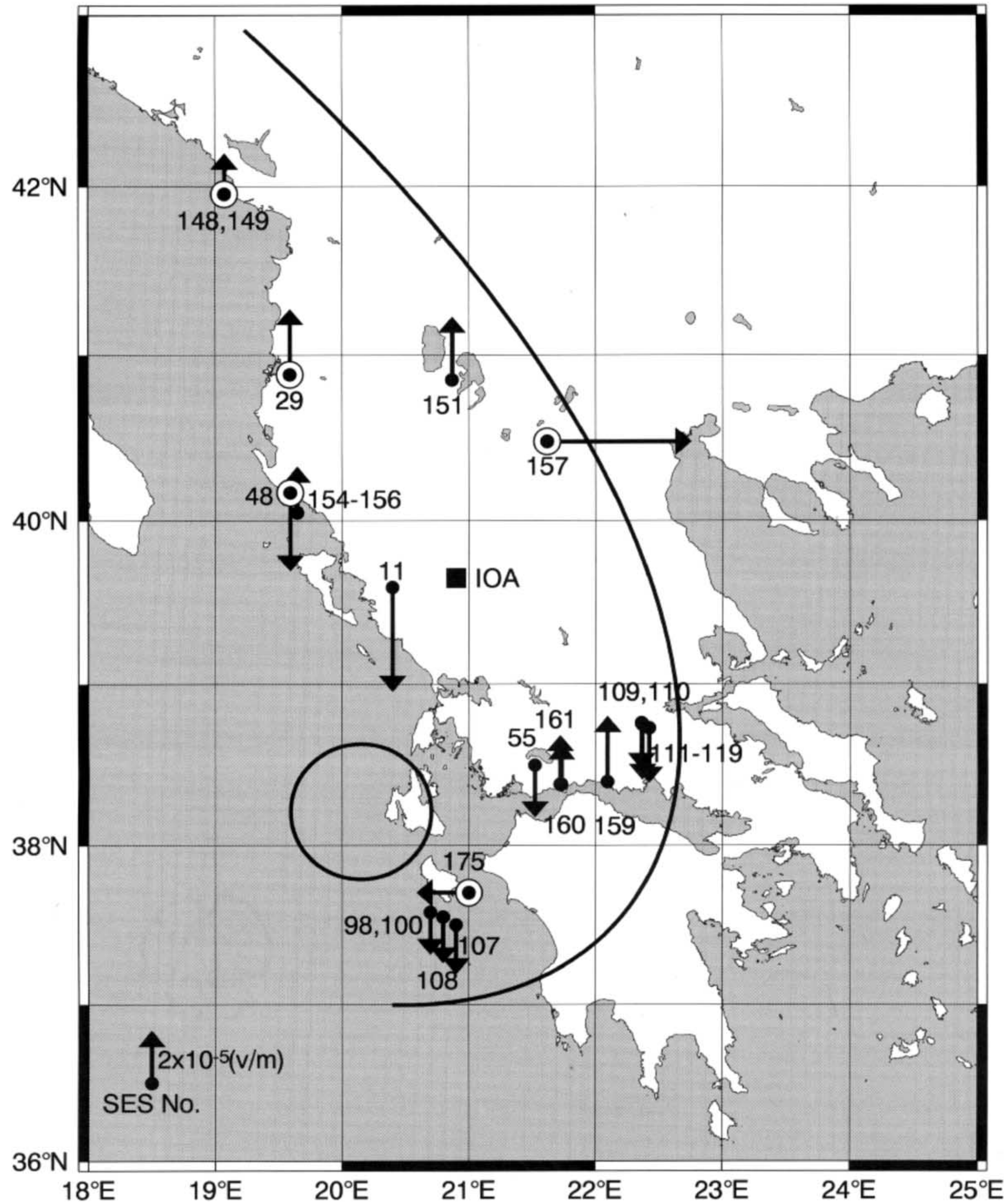

Fig. 12. Reliable SES–EQ correlations and the selectivity map of IOA as of 1984 according to the present authors. Epicenters are after NEIC-PDE catalogue. Five cases, which agreed with VAN's reliable correlations, are marked by double circles.

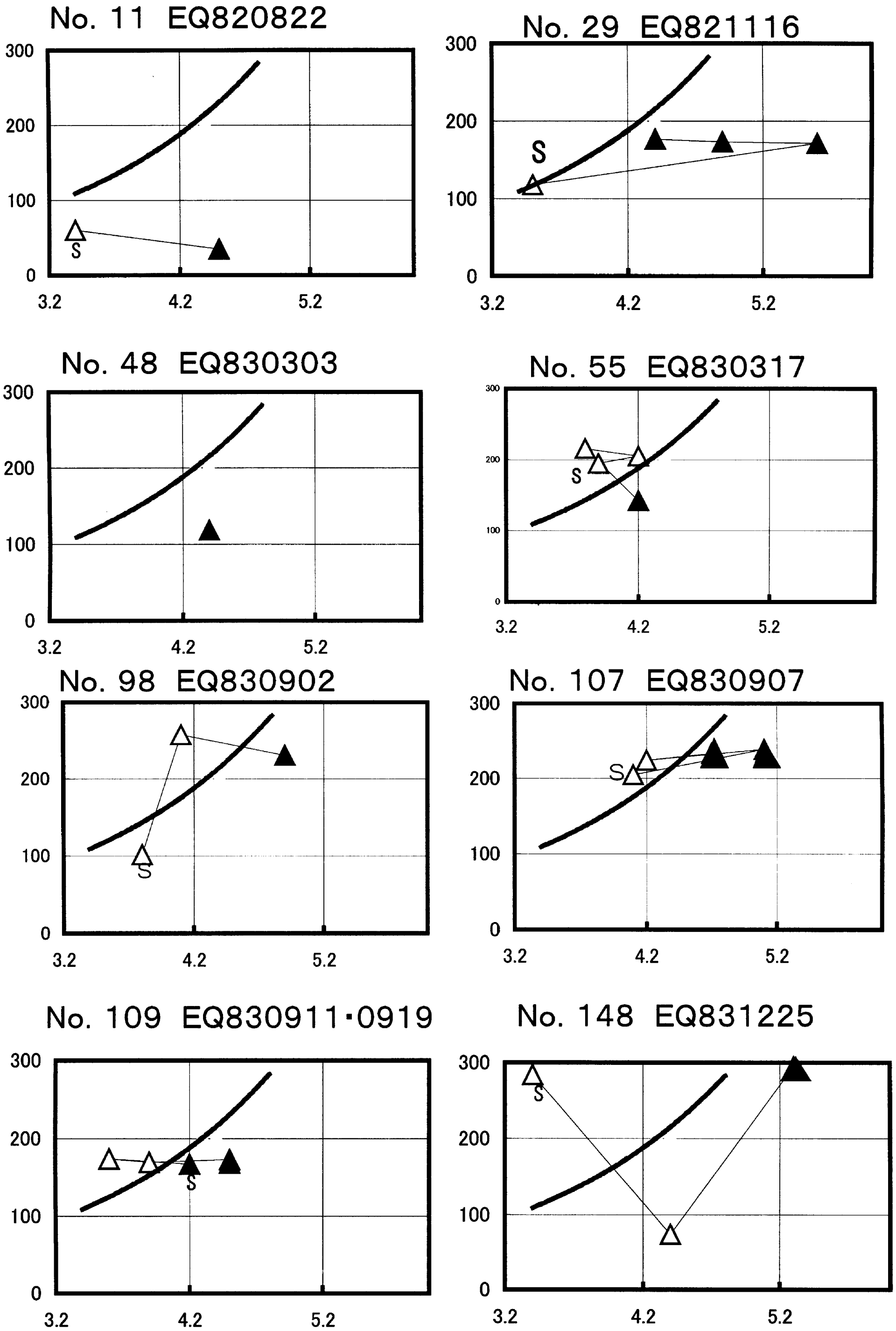

Fig. 13. Epicentral distance–magnitude diagrams, using NEIS-PDE catalogue, of EQs selected for our correlations. Vertical axis in km; horizontal axis in mb. Thick line is the same as that in Fig. 10, only displaced horizontally to adjust the difference between mb and Ms(ATH) scales.

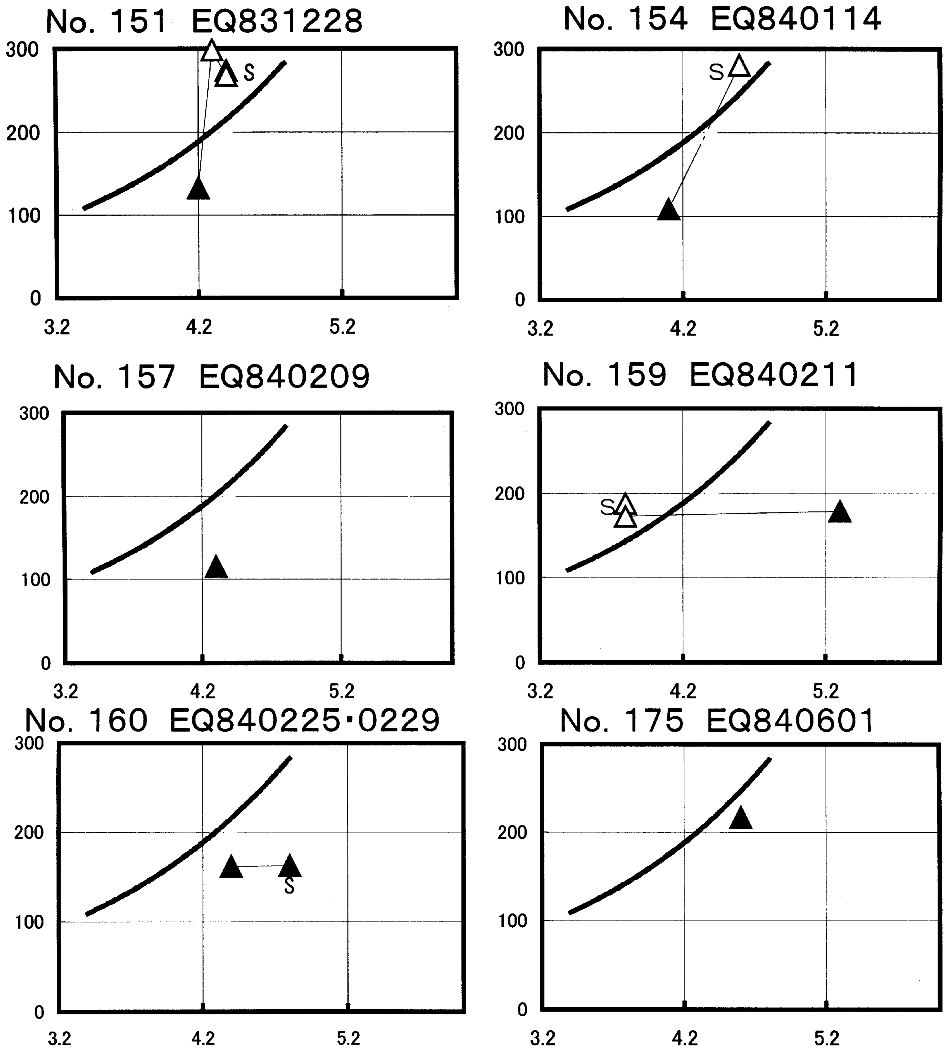

Fig. 13. *continued.*

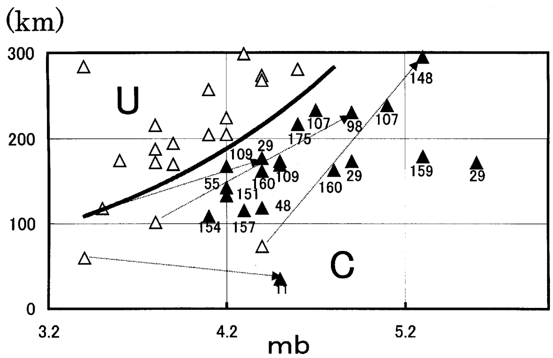

Fig. 14. Combined epicentral distance–magnitude diagrams for our correlations. Vertical axis in km; horizontal axis in mb.

4. Use of long dipole information for improved epicenter estimation

With the information shown in Fig. 8, it must have been difficult to make definite predictions at that time. In fact, the internal test prediction telegrams based on SESs No.157 and No.164 were vague. For the purpose of better epicenter estimation, the direction or the polarity of SES was considered to provide additional information. The short dipole observations did not provide enough information as seen in Figs. 8 and 12: in many cases, short-dipole SESs at IOA were detected only on NS dipoles. Exact reasons for this are not clear to the present authors. Since, by definition, SESs were always signals simultaneously detected on multiple dipoles, they can not be electrode noise. One of the reasons for this seemed to be concerned with a practical matter for signal recognition. The magnetotelluric changes are dominantly in the ENE–WSW direction at IOA, mainly reflecting the ocean-continent boundary to the west. Signals on the EW dipoles tend to be buried in magnetotelluric noise. Other reasons may be more complicated; namely the polarization of SESs may be influenced by the position of their source(s) relative to the station. Indications that the direct sources of SESs at IOA may be near the station have been reported based on a study of SES polarization (Uyeshima et al., 1998). Even if the primary sources are in far focal areas, SESs are now considered to travel through conductive channels and the outlets of the current are closer to the observation station (Varotsos et al., 1998b). SES polarization in any case is expected to be further affected by local heterogeneous electrical structures (Kanda et al., 2000). Such problems, however, are beyond the scope of this paper.

At IOA, long dipoles were installed in July, 1985 to help discriminate the noise from sources that are more distant than the scale of short dipole network. One of them was a 2.1 km long dipole installed between the IOA station and the town of Perama and oriented in $\Theta = \mathrm{N}30^\circ\mathrm{E}$ (Fig. 4). The VAN group devised a practical method of better characterizing SES using this long dipole data. Namely, they take the ratio of the potential differences observed with the NS short dipole, V_{NS}, and with the N30°E oriented long dipole, V_{long}. If we are measuring a uniform electric field $\mathbf{E}(E_{\mathrm{EW}},\ E_{\mathrm{NS}})$ in a homogenous and isotropic medium, the potential difference measured with dipoles should scale with the dipole length. In such a case, the ratio can be expressed as,

$$\left(V_{\mathrm{long}}/V_{\mathrm{NS}}\right) = \left(L_{\mathrm{long}}/L_{\mathrm{NS}}\right)[\cos\Theta + (E_{\mathrm{EW}}/E_{\mathrm{NS}})\sin\Theta] \quad (1)$$

where L_{long} and L_{NS} are the length of the long and NS short dipoles.

Since Θ and $(L_{\mathrm{long}}/L_{\mathrm{s}})$ are constant, $(V_{\mathrm{long}}/V_{\mathrm{NS}})$ can be a good measure of $(E_{\mathrm{EW}}/E_{\mathrm{NS}})$ because it amplifies the latter almost by the ratio $(L_{\mathrm{long}}/L_{\mathrm{NS}} \fallingdotseq 20) \times (\sin\Theta = 1/2) \fallingdotseq 10$. Obviously, the underground structure is neither homogeneous nor isotropic. Therefore, the ratio $(V_{\mathrm{long}}/V_{\mathrm{NS}})$ is considered to be merely a parameter, sensitive to $(E_{\mathrm{EW}}/E_{\mathrm{NS}})$. We call $(V_{\mathrm{long}}/V_{\mathrm{NS}})$ the directional parameter or DP hereafter.

Table 3 lists all $mb \geqslant 5$ EQs in the region in NEIC-PDE catalog for January 1988–December 1997. The VAN group correlated them with SESs as also listed (Uyeda and Al-Damegh, 1999; P. Varotsos, private communication). From these SES data, we have computed the DP values, namely the ratio of V_{long} and V_{NS} readings. Long dipole ($L = 2.1$ km) and short dipole ($L = 50$ m) data were used when available. Otherwise, other dipole data were also used. Fig. 15(a) shows the

Table 3
All mb ⩾ 5 EQs in NEIC-PDE catalogue for the region (May 1988–December, 1997) and correlated SES data

EQ						SES											
No.	Date	Time (GMT)	Lat. N	Lon. E	mb	Date	Time (LT)	Duration	E–W (10^{-6} V/m)		N–S (10^{-6} V/m)	Long dipole (10^{-6} V/m)					DP
									50 m	50 m	50 m	100 m	184 m	*L* (2.1 km)	*L*′ (1.1 km)	(5 km)	
1	EQ880109	1:02:46	19.63	41.246	5.3	SES871230	22:17	5	0		−9						
2	EQ880518	5:17:42	20.479	38.418	5.4	SES880515	8:38	3	−5	−5	8.5	10.5	nw	3.57			8
3	EQ880522	3:44:15	20.464	38.409	5	SES880521	6:51	3	0	0	−5.5	−6.5	nw	−5.93			23
4	EQ880922	12:05:40	21.089	38.022	5	SES880831	12:25	2	20	22	15	14	11.7	16.35			27–37
							12:52	2	20	31	15	15	11.1	19.34			27–37
							13:06	1	18	20	12.5	9	5.97	13.39			27–37
							13:08	2	18	25	14	12	10.9	16.36			27–37
5	EQ881016	12:34:05	20.932	37.938	5.5	SES880929	15:40	310	0	1	−7.5	−6	−5.43	−13.39			56
6	EQ890607	19:45:53	21.62	38.057	5	SES890601	21:12	3	0	0	−8.5	−9.5	−6.52	−4.46			12
7	EQ890820	18:32:29	21.203	37.278	5.4	SES890814	22:02	1	−5	−8	6	5	5.43	7.44			37
8	EQ890824	2:13:15	20.183	37.995	5.1	SES890823	7:56	4	12		5						
9	EQ900616	2:16:21	20.528	39.258	5.6	SES900524	18:45	15	−10		−7						
10	EQ910626	11:43:35	21.098	38.435	5	SES910513	15:45	10	−5		10			70.2			59
11	EQ920123	4:24:15	20.324	38.351	5.1	SES911224	15:40	~80	~0	~0	nw	−5–(−8)	−3.8	−10.0–(−12.4)	nw	nw	25–52
						SES911230	18:30	~10	~0	~0	nw	−3–(−4)	nw	−4.8–(−6.2)			25–52
12	EQ920621	18:59:05	19.807	39.137	5	SES920524	19:47	1.5	~0	~0	?	1.5~2	1.36	3.1			32–53
							20:05	1.5	~0	~0	?	1.5~2	1.36	3.8			32–53
13	EQ930305	6:55:08	21.505	37.178	5.2	SES930129	6:05	1.5	~0	~0	−5	−4	−3.2	Out	−5.0		26
14	EQ930318	15:47:00	22.155	38.34	5.7	SES930127	7:38	3	~0	~0	−12	−12.5	−12.2	Out	−21.0–(−25.7)	Out	35–43
15	EQ930326	11:58:15	21.391	37.589	5.2	SES930216	8:45	37	~0	~0	−10	−11	−10.3	−11.9	−12.4	−6.8	33
16	EQ930613	23:26:40	20.495	39.363	5.3	SES930402	4:35	3	−2		−5						
						SES930610	18:22	2	20	16	12	11	9.8	12.4–15.2	18.6–24.8	5.2 (10)	16–40
17	EQ930714	12:31:49	21.756	28.224	5.3		18:50	5	8	6	8	16–18	7.6	6.7–11.9	15.2	4?	23–47
18	EQ931104	5:18:37	22.002	38.372	5.1	SES931023	6:00	1	−14			−12.5	−8.1		−10.5–(−11.9)		18–20
19	EQ931224	21:53:19	19.815	40.158	5.2	SES931114	5:50	1.5	~0	~0	−10	−11	−9.2	−12.9	−13.8	−6.4	25–26
							~8:00				Almost the same						
20	EQ940225	2:30:51	20.532	38.854	5.3	SES940206	5:50	153	0	0		−7.8				−13.8	32–61
							12:28	8	0	0		−10–(−12.5)				−8–12	32–61
21	EQ940416	23:09:33	20.617	37.43	5.3	SES940225	~4:00	~0.5	−26	−28	−10	−10	No?	−10.5	−12.4	−10.4?	22–30
						SES940317	~15:10	~2	−14	−16	−6	−7	−4.3	−8.6	−23.8	−5.2	22–30
22	EQ950513	17:47:12	21.7	40.15	6.2	SES950419	6:30	67	0	0	−10	−10	−10	−11.9	−13.4	−12.5	22
23	EQ971106	6:10:29	22.28	38.43	5.5	SES971003	18:54	0.5	−6	−7.5	−5	−6.3	−3.1	−3.7	−5.2	−3.8	12
24	EQ971118	22:07:42	20.66	37.57	5.9	SES971005	5:00	1.5	0	0		−3.1	−3.0	−3.7	−3.7		26
							7:32	40	0	0		−3.0	−3.0	−3.7	−4.4–(−5.2)		26

nw: Not working.

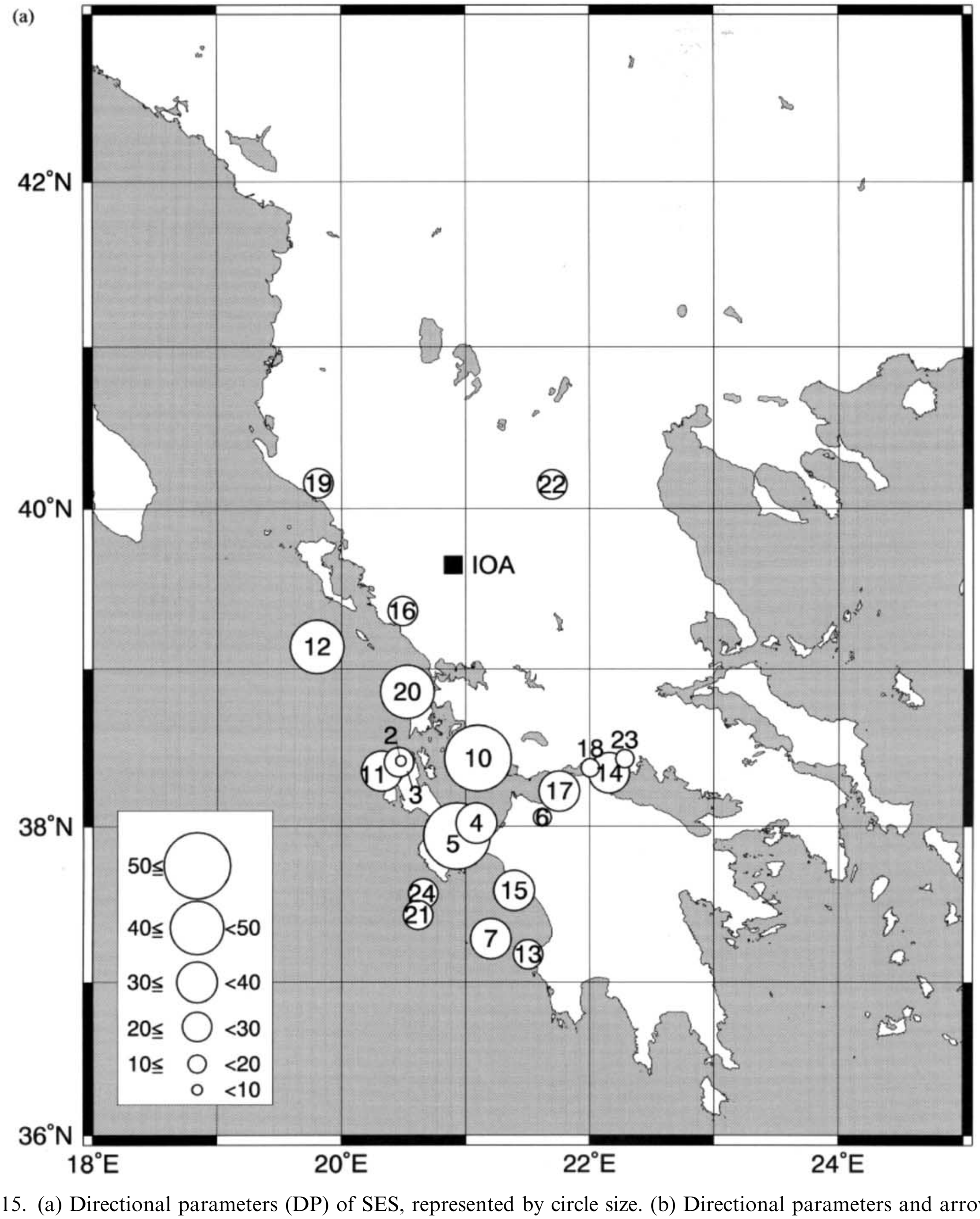

Fig. 15. (a) Directional parameters (DP) of SES, represented by circle size. (b) Directional parameters and arrows of short dipole SES in Table 3. EQs in Table 3 without DP values are represented only by arrows with EQ numbers. White arrows are from Fig. 8. Note that all arrows are normalized to have the same length, because the length depends on the EQ magnitude and should have little to do with the directional properties of SES useful for epicenter estimation. Arrow for EQ No. 17 (see figure (a)) is displaced for clarity. This also shows the selectivity map of IOA as of end of 1997.

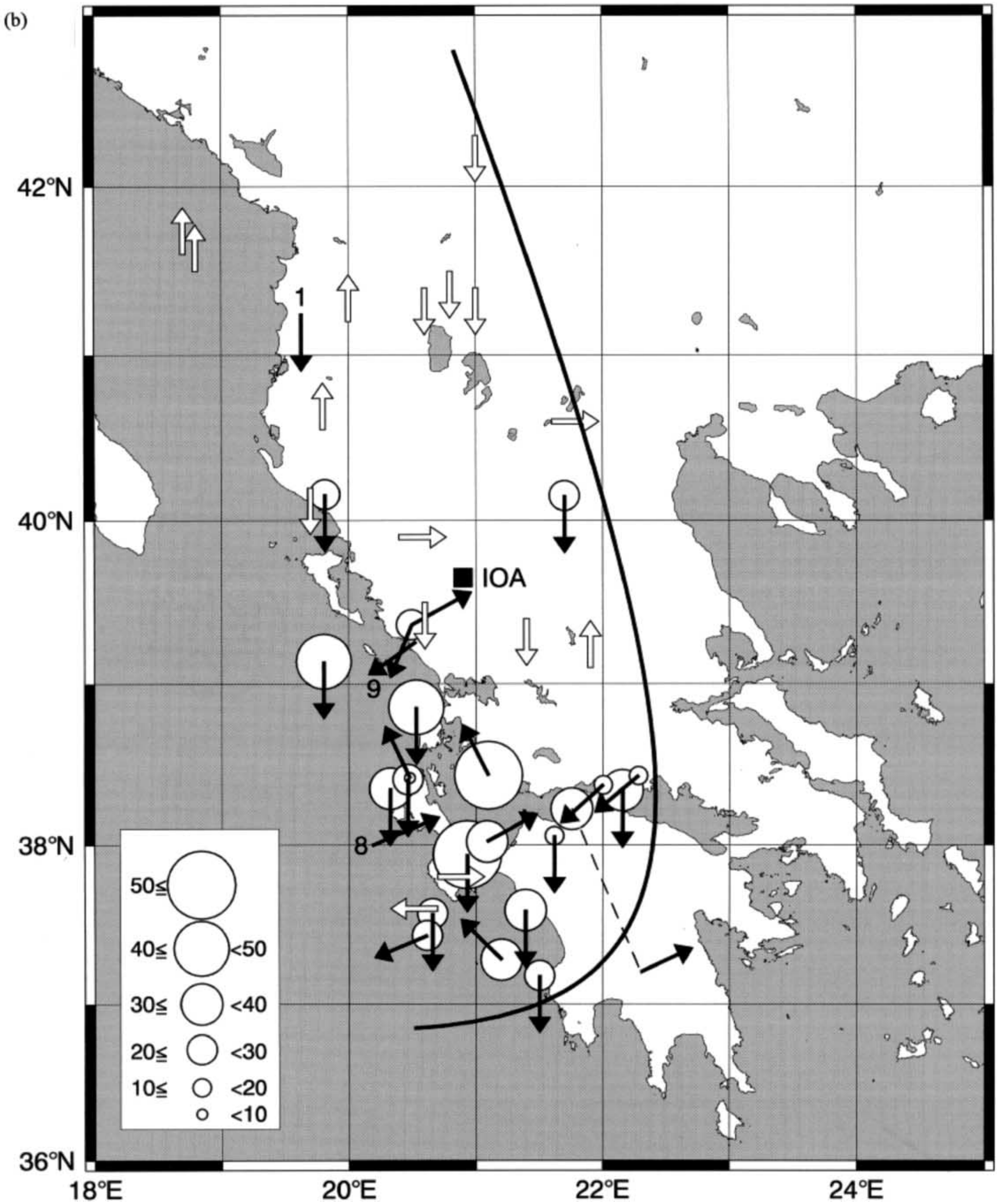

Fig. 15. *continued.*

DP distribution, where DP values are represented by the size of circles containing the EQ numbers in Table 3. Large DP values are found along the coast line SW of IOA. One can see in Table 3 and Fig. 15(b) that the direction of short dipole SES and DP are not uniquely correlated. The selectivity map (Fig. 15(b)) is similar to previous selectivity maps (Figs. 8 and 12), except for the Kefallinia area, which became IOA sensitive in 1988 (Uyeda et al., 1999). It appears that the combination of short dipole SES directions and DP values helps make better epicentral predictions. Unique epicentral prediction, however, still seems difficult. For instance, southward SES and a moderate value of DP are found in both the northern and southern areas. This must be one of the reasons why some of the VAN predictions had to be double predictions.

Let us consider the cases of the last three EQs in Table 3. On 19 April 1995 (also on 18 April), they observed SES activity pointing southward with DP = 22. They made a double prediction (see p. 62, Varotsos et al., 1996); one in the area of EQ No. 5 in Fig. 15a and the other a few tens of km NW of IOA. They considered the latter was more compatible with data. From the data shown in Fig. 15 alone, such a prediction does not seem to be uniquely derivable. In this particular case, the experience of Vartholomio EQ (No. 5) must have influenced their inferences. Preference of the latter epicentral prediction was based on the fact that the long dipole data indicated a closer epicenter. Actual EQ (No. 22) occurred in Grevena area NE of IOA, which better fitted their preference for a nearer epicenter, but not NW of IOA. It was natural that they did not predict the NE area because this area has been devoid of large EQ for centuries. Because the VAN prediction process requires empirical correlations between SESs and EQs to form the selectivity maps, a region with no EQs will not appear on any selectivity map.

Then, there was a period of two and half years of no SES and no EQ until they observed SES activity on 3 October 1997 (short dipole in SW direction, DP = 16) and 5 October 1997 (short dipole SES in NS direction, DP = 26). They predicted the epicenters of EQ No. 23 and EQ No. 24 in the area just east of No. 18 and west of No. 15, respectively (Varotsos et al., 1998a). SES data are certainly compatible with each other among these EQs and the actual epicenters were not far from predicted places.

5. Conclusions

The way the VAN group had been finding sensitive stations and constructing the selectivity maps has been described only briefly in their publications. In order to help the community understand the reality of the VAN operation, we have tried to duplicate their history through looking at their early work. We first examined their early original work-sheets of candidate SES at the IOA station and earthquakes (EQs) in 1982–1984; the result showed that in most cases, the SES–EQ correspondence was not definitive. They recognize this also: namely, from about 180 candidate SESs and almost 200 candidate EQs, they only identify 14 reliable cases even in hindsight. Having found that a complete reproduction of their historical developments cannot be done because of insufficient information, we tried independently to make the correlations. We also came up with 14 cases of "reliable" correlation. Only five cases, however, were common to both sets of correlations. Reliable correlations have SESs isolated in time and EQs isolated in time, space and magnitude. These correlations were more or less unique, although this does not mean that they were necessarily physically or statistically meaningful.

The preliminary selectivity map of the IOA station based on the above correlations was covering a quite wide area and hardly sufficient to allow epicentral prediction with accuracy. To improve the method, the VAN group has made use of the direction of SES. However, observed SESs of short dipoles at IOA were often biased to give only NS component. In order to help characterize SESs, the ratio of SES amplitudes of long dipole and NS short dipole (directional parameter, DP) was employed. Combined use of DP values and SES vectors has improved epicenter prediction to some extent.

Acknowledgements

The authors are grateful to Professor P. Varotsos for providing them with unpublished detailed information on the VAN operation at the Ioannina station in early stage, including their original work-sheets, strip chart SES records and inter-VAN telegrams. Reviewers, Professors H. Kanamori and S. Park are also thanked for their criticism and many useful comments.

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