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Relationship of M_L^{SM} and magnitudes determined by regional seismological stations in South-Eastern and Central Europe

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We show how by comparing M_L^{SM} (computed from strong motion accelerograms within 150 km from the epicenter) and M_{STA} (reported by different seismological stations in Yugoslavia, Italy, Albania, Greece, Austria and Czechoslovakia) it is possible to calibrate amplitude-distance attentuation equations used in M_{STA} definitions. This, more accurate, magnitude determination for regional networks is essential for: (1) better and more accurate integration of the engineering estimates of siesmic risk; and (2) for more accurate and quick estimation of strong motion amplitudes in epicentral region of destructive earthquakes.

INTRODUCTION

In engineering estimation of seismic risk[1,2] classification of earthquake size in terms of a magnitude scale constitutes the essential first step in the description of the surrounding seismic activity. There are many regions where the local intensity scales continue to be the only way to describe this local level of shaking,[3] but the growth and better organization of local seismological networks is slowly spreading through many active regions of the world. For engineering estimation of seismic risk it is essential to establish consistent, homogeneous and complete catalogues of earthquake activity over as long periods of time as possible.

Since the early 1930s, with the first development of magnitude scale,[4] and during the following 60 years many different magnitude scales have been proposed and refined. While many new ideas and improvements have contributed to the physically more meaningful and accurate description of the 'size' of an earthquake, engineering risk studies continue to be confronted with lack of uniformity of the data base, lack of precision in relative calibration among different magnitude scales and with almost total lack of calibration relative to the amplitudes of strong shaking near earthquake source. Since the local geologic conditions can have a profound effect on the differences between the near source and distant estimates of magnitude,[5,6] in this paper we propose a method for relative calibration of the distant magnitude estimates.

At shorter epicentral distances (0° to 3°) the S_g (shear wave in the crust propagating directly from source to station) and L_g (higher modes of Love and Rayleigh waves with periods near 1 sec) waves dominate in the records[7,8] and are used in

$$M = \log (A/T) + \sigma \tag{1}$$

to determine the earthquake magnitude. In (1), A represents the peak response amplitude, T is period in seconds associated with peak reponse A and σ incorporates empirically estimated correction factors which include: differences in the predominant period T, regional differences in attenuation with distance, $\mathscr{D}$, different magnitude range, calibration procedures, instrument response, and differences in the average focal depth.[9]

The first definition of magnitude scale employed an

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Table 1.

No.	Year	Mo	Dy	Hr	Mn	Lt(N)	Ln(E)	H	Mag	Int	MLSM	TRI	ZAG	TTG	BLY	LJU	BEO	FIR	SDA	PRT	RMP	VLO	KCA	PS1	THE	TIR	PRA	SK1	SK2	SK3	FOG	ORI	SGG	VKA	SAR
2	1976	7	14	5	39	46·35	13·31	6	4·4		3·96	4·2	4·4	4·1						4·2	4·7						4·3		4·2	4·2				4·7	4·2
3	1976	9	11	16	31	46·30	13·22	7	5·1	7·5	4·71	5·1	5·4	5·5	5·5					5·6							5·5		5·3	5·5					5·6
4	1976	9	11	16	35	46·24	13·17	11	5·6	9·0	5·51	5·6	5·4	5·8	5·6					6·1	5·9						5·6		5·6	5·8					5·8
5	1976	9	11	16	48	46·29	13·17	1	4·3											4·1	4·2						4·1							4·4	
6	1976	9	12	19	53	46·29	13·24	6	4·5		4·14	4·1	4·3	4·6						4·7	4·8						4·6		4·6	4·8					4·6
7	1976	9	13	18	54	46·33	13·21	4	4·4		4·45	4·3	4·1	4·4				4·4		4·5	4·6						3·8		4·1	4·3				4·8	4·2
8	1976	9	15	3	15	46·28	13·18	9	5·8	9·0	5·94	5·8	5·9	6·5	6·3			5·9		6·1	6·1						6·1			6·5					6·3
9	1976	9	15	4	38	46·31	13·17	7	4·8	7·0	4·55	4·7	4·6							5·0	5·0						4·3		4·6	4·7					4·5
10	1976	9	15	4	58	46·33	13·21	5	4·6		4·25	4·3	4·3							4·7	4·7						4·0		4·2	4·3					
11	1976	9	15	9	21	46·33	13·15	2	6·1	9·5	6·04	6·1	5·8	6·3	6·2					6·2	6·0						6·0			6·3					5·8
12	1976	9	15	11	11	46·33	13·24	8	5·0	7·5	4·65	4·5	5·0	5·2						5·0	5·0						5·0		4·9	5·0					4·9
14	1977	9	16	23	48	46·28	12·97	11	5·3		4·80	5·2	5·1	5·5	5·3			5·4		5·3	5·4						5·1		5·3	5·4					5·2
15	1977	9	28	1	43	46·29	13·05	17	4·2		4·32	4·2	4·0	4·1						4·1	4·4						3·4		3·5	3·8				4·0	3·9
16	1978	1	1	4	23	43·30	17·60	20	3·8	5·5	3·52	5·0	4·0	4·0	3·8	4·0		4·0		4·3								3·3	3·6	3·5					
17	1978	2	20	12	13	46·48	13·25	0	4·0	6·0	4·62	4·0	3·7	4·2						4·1				4·0											
18	1978	3	16	6	8	43·10	18·03	20	4·0	6·0	3·94	4·6		3·6	4·1				3·5									3·4							4·0
21	1978	12	17	2	16	43·44	17·38	16	4·5		4·22	5·5		4·2	4·5	4·5				4·2	4·9			4·6				4·0						4·1	
22	1979	2	17	22	6	44·69	17·25	5	3·4		3·35	3·8			3·4	3·2																			
23	1979	3	31	15	55	41·88	19·07	6	4·0		4·09	5·0		3·8		3·9						3·9	3·8						3·9	4·1		3·5	4·2	3·6	
24	1979	4	9	2	10	41·90	19·05	0	5·2	7·5	5·33	5·9	5·2	5·1	5·2	5·4					5·3			5·6	5·4		5·2	5·4						4·9	5·2
26	1979	4	15	6	19	42·02	19·07	13	7·0	9·5	7·09	6·9	7·0			7·2				7·0	6·7				7·1		6·9		7·2						
27	1979	4	15	6	31	42·16	18·74	10	4·9		4·87				4·9												4·7				4·9				
28	1979	4	15	7	11	41·98	19·18	11	4·2		4·18												4·3			4·6									
29	1979	4	15	7	25	41·94	19·47	10	4·1		4·20																								
31	1979	4	15	8	8	42·24	18·65	10	4·4		4·07	4·9			4·4					4·6	4·6			4·5		4·1			4·1	4·2	4·4				
32	1979	4	15	8	13	41·92	19·24	26	4·3		4·35		4·4							4·8	4·7			4·7	4·6	4·2			3·9	4·2	4·3				
37	1979	4	15	10	25	41·91	19·40	15	4·9		4·85	5·5	5·1		4·7					4·8	5·0			5·1	5·1	4·6	4·4		4·5		4·9			5·0	
38	1979	4	15	11	7	42·08	19·06	6	4·2		4·37	4·9	4·2							4·6	4·5				4·5	3·9	3·8			4·0				4·0	
39	1979	4	15	11	42	41·93	19·41	10	3·7		3·58	4·9									4·6			4·3		4·3			3·2						
40	1979	4	15	12	43	42·08	19·19	12	4·4		4·09	5·0	4·4								4·4			4·4	4·7	4·2		4·0		4·2				4·1	
41	1979	4	15	13	24	42·41	18·74	10	4·3		3·66	4·9	3·8								4·6			4·4		4·3				3·5					
42	1979	4	15	14	43	42·26	18·71	9	5·8		5·58	6·3	5·9	5·8	5·7	6·0		5·0		5·8	5·7			5·6	5·8	6·0	5·8					4·9		5·8	
43	1979	4	15	17	52	42·55	18·55	9	4·1		3·64	4·9	4·1	4·0	4·0					4·6	4·5					4·2			3·1						4·2
46	1979	4	15	20	49	42·00	19·21	14	4·3		4·0·		4·3	4·3	4·3					4·8	4·6	4·3	4·0	4·7	4·7	4·1				3·9	4·3	4·2		4·2	4·4
49	1979	4	16	7	56	41·79	19·56	17	4·2		4·26	4·6	4·7	4·0	4·3					4·6	4·5		4·1		4·9	4·1						4·2		4·4	4·5
51	1979	4	16	10	4	41·92	19·24	10	4·9		5·17	5·7	5·3	4·6	5·1			4·9		4·9	5·1		4·4	5·4	5·3	4·4	4·8	5·8				4·8		5·1	4·9
53	1979	4	16	14	30	42·00	19·03	15	4·1		4·21	4·7	4·0	4·2	4·2						4·4	4·2	3·7			4·0						3·9		4·0	4·3
55	1979	4	16	15	51	41·81	19·37	10	3·8		3·68	4·1	4·0		3·6							4·2	3·2		4·6		4·0								3·9
56	1979	4	16	23	0	41·86	19·38	11	4·2		4·48	4·6	4·0	3·7	4·2	3·9				4·4	4·5	4·5	4·2	4·4	4·8	4·1						4·0		4·0	4·3
58	1979	4	17	3	53	41·80	19·48	10	4·2		4·14	4·9	4·2	3·4	3·7	4·2						4·3	4·1		4·6	3·9				4·8		4·6		4·0	4·0
59	1979	4	17	5	39	42·45	18·62	0	4·9		4·61	5·9	5·2	4·2	5·1	4·9		4·8		5·2	5·4	5·0	4·7	5·5	5·1	5·2	5·0							5·1	
61	1979	4	17	18	6	42·04	19·05	1	4·0		4·22	4·9	4·2		4·1	3·7							3·7		4·5	4·0		4·0					4·2	3·8	4·5
64	1979	4	18	2	45	41·89	19·10	8	3·7		3·63	4·6	4·0		3·8	3·7						4·0	3·6			3·6				3·7			4·2		3·9
65	1979	4	18	3	50	41·91	19·14	7	4·1		3·95	4·6	4·3	4·1	4·4						4·4	4·2	4·0	4·7	4·8	4·0			4·2		4·2		4·4	4·1	4·3
67	1979	4	18	15	19	46·34	13·29	21	4·8	7·0	4·78	4·8	5·0		4·7	5·0		5·1		4·9	5·1			4·7			4·9							5·0	4·0
68	1979	4	18	19	51	42·01	19·06	5	4·6		4·56	5·2	4·9	4·2	4·3	4·7				4·7	4·8	4·6		4·6	4·9		4·6			4·7	4·8	4·1	4·6	4·7	4·5
69	1979	4	19	0	17	41·90	19·18	10	4·5		4·71	5·2	4·9		4·4	4·6				4·5	4·6	4·6	4·2	4·9	4·9	4·3				4·5		4·4		4·7	4·6
70	1979	4	19	5	42	42·04	19·03	2	4·6		4·63	5·2	5·0	4·3	4·6					4·6	4·6	4·6	4·3	4·6	4·8	4·3	4·5			4·6	4·6			4·8	4·8
71	1979	4	19	7	7	42·01	19·02	3	4·0		3·78		4·2	4·0	4·2	3·9					4·4	4·2	3·6			3·8				3·9			4·1		4·4
72	1979	4	21	2	38	41·98	19·20	20	4·3		4·90	5·2	4·3	4·3	4·4	4·1				4·8	4·6	4·6	4·6	4·7	4·7	4·3				3·8	4·5		4·4	4·1	4·3
73	1979	4	21	4	33	41·80	19·18	5	4·3		4·17	5·1		4·2	4·2	4·4				4·8	4·5	4·4	4·3		4·7	4·1	4·1		4·1	4·3		4·1	4·4	4·5	4·2
74	1979	4	21	4	54	41·83	19·16	5	3·9		3·78	5·1		4·2	4·1					4·6	4·4	4·1	3·6	4·3	4·6	4·0			3·8	4·0		3·7		4·1	4·0
78	1979	4	22	6	32	41·92	19·24	5	4·5		4·52	5·2	4·7	4·2	4·5	4·4				4·9	4·6	4·4		4·6	4·8	4·4	4·2			4·5	4·3		4·4	4·5	4·5
79	1979	4	22	7	32	41·78	19·32	16	4·0		3·52	5·0		4·0									4·0						3·4	3·6		3·9	4·0		
80	1979	4	23	12	52	41·92	19·26	8	3·2		2·81															3·2				3·1					
81	1979	4	24	22	26	41·94	19·28	10	3·6		3·37	5·0			3·9				3·3			3·7	3·4			3·5			3·2	3·7					3·9
82	1979	4	25	6	36	41·92	19·25	6	3·8		3·96	5·0										4·4	4·1	5·1	4·7	4·2			4·2	4·3		4·0		4·0	
83	1979	4	25	15	14	41·83	19·19	11	3·8		3·85	5·0				4·1			3·7			4·0	3·8			3·6			3·8	4·0			4·1	4·2	3·9

84	1979	4	25	19	12	41·85	19·26	11	3·6		3·59	4·9				4·0			3·6			3·9	3·5	4·6		3·5			3·4	3·5					
85	1979	4	28	3	38	42·19	18·81	2	4·5	7·0	4·21	5·2	4·7		4·4					4·8	4·8				4·6	4·4	4·2	4·4		4·5	4·4		4·3	4·6	4·5
86	1979	4	29	10	24	42·00	19·23	10	3·9		3·52	5·1	4·0		4·0	4·2						3·7				3·5				3·9				3·9	4·1
87	1979	4	30	17	0	42·27	18·82	4	4·5		3·72	5·1			4·5	4·1			3·9	4·7	4·6	4·7	4·0	4·8	4·7	4·2			4·0	4·2			4·2	4·1	4·1
88	1979	5	1	6	39	41·93	19·26	4	3·2		3·32								3·4							3·4			3·2	3·3			3·9		
90	1979	5	3	16	39	41·85	19·13	5	3·5		3·61			3·0	3·6				3·7				3·4			3·6		4·0					4·4		3·6
92	1979	5	12	3	30	42·26	18·91	9	5·2		5·25	5·8	5·5		5·1	5·5		5·5		5·2	5·2		4·9	5·4	4·9	5·3	4·9			5·0		4·5	5·2	5·2	5·2
93	1979	5	14	9	53	41·93	19·19	10	4·6		4·85	5·4		4·6	4·7	5·0				4·8	4·8	4·4	4·1	4·9	4·9	4·2	4·4		4·5	4·5	4·6	4·2		4·8	4·6
94	1979	5	20	8	45	42·19	18·82	5	4·3		4·42			3·9		4·3			3·3	4·8	4·8		4·1	4·8	4·5	4·5			4·3	4·5	4·5			4·2	4·5
95	1979	5	24	17	23	42·15	18·76	5	6·2	7·5	6·25	6·8			5·7	6·5		5·8			6·2			5·8	6·3	6·2	6·4	6·1							6·1
96	1979	7	20	2	56	41·86	19·21	5	3·6		4·10		3·1		3·5				3·6			3·9	3·6			3·7			3·4	3·6					
100	1979	9	21	12	2	41·95	19·36	4	4·2		4·11	4·7	4·0		4·0	4·2						4·4	4·2		4·6	4·2			4·1	4·2			4·5	4·1	4·0
101	1979	11	6	8	5	41·90	19·26	6	3·1		3·58	4·1				3·1						3·9	3·3						3·0	3·5					
102	1979	11	9	1	48	41·88	19·30	7	4·1		4·32	4·6	3·9		4·1	4·3	3·9		3·7			4·5			4·5	3·8			4·1	4·2			4·4	3·8	4·1
103	1979	11	9	4	20	41·87	19·24	4	3·7		3·35								3·5			4·4	3·7						3·7	3·8			4·1		
104	1979	11	10	4	19	41·90	19·37	6	4·2		5·11			4·1	4·3	4·5			3·8			4·4	4·0		4·5		3·9		4·1	4·3	4·0		4·5	4·0	
105	1979	11	20	18	31	42·01	18·96	8	4·5		4·77	4·6							3·8			4·4	3·8		4·5		3·8		3·9	4·1				3·7	3·8
106	1980	5	21	9	22	43·33	21·00	7	3·8		3·52			3·8	3·8				3·4				4·0					3·6		3·3				3·7	
107	1980	5	23	12	26	43·28	21·04	0	4·5		4·81	5·1	4·9	3·8	4·6	4·7			3·9			5·0	4·7				4·5			4·5			4·4	4·6	
108	1980	5	23	12	37	43·19	21·02	5	3·2		3·48								3·0			3·2	3·5					2·9		3·0					
109	1980	5	25	6	3	43·26	21·06	13	3·6		4·14												3·6					3·2		3·2				3·7	
110	1980	5	25	7	8	43·27	20·95	9	3·6		3·53				3·9				3·3				3·5					3·2						3·6	
111	1980	5	26	0	25	42·87	20·98	10	3·4		3·32																								
113	1980	6	1	21	24	43·28	21·01	8	3·4		3·93			3·0		2·9			3·3				3·8					3·1		3·5				3·6	
114	1980	6	3	19	8	43·25	21·00	10	3·5		3·58	4·3			3·4	3·4			3·4				3·9							3·3				3·6	
115	1980	6	4	3	21	43·27	20·99	4	3·1		3·30																	2·7							
116	1980	6	9	8	11	43·07	20·73	10	2·9		3·21																								
117	1980	6	10	21	25	43·34	21·05	10	4·1		4·07	4·5		3·6					3·6			3·9	4·4						3·5					3·9	
118	1980	6	12	23	46	43·05	20·98	12	3·5		4·11			3·1									3·1							3·0					
119	1980	6	14	2	20	43·05	20·97	18	3·3		3·53			3·1		3·1			3·0				3·3						3·0	3·2					
120	1980	6	17	9	52	43·25	20·95	10	3·7		3·96	4·2		3·7	3·9								4·0					3·3							
121	1980	6	17	22	14	43·23	20·95	10	3·7		3·81	4·3		4·0	3·9				3·7				4·3					3·6					4·2	3·7	
122	1980	6	19	1	47	43·19	20·92	10	3·6		3·95			3·7	3·7	3·5									3·5	3·0	3·1			4·1	3·7				
123	1980	6	19	4	42	43·27	21·07	10	3·5		3·28			3·3	3·4													3·2	2·8	2·9					
124	1980	6	28	6	10	43·22	20·94	6	3·4		3·59			3·3									3·5					3·1							
125	1980	6	29	5	52	43·21	20·88	9	3·7		3·49			3·4	3·7	2·9			3·5				4·1					3·3					4·2	3·8	
126	1980	7	1	6	43	43·26	20·96	9	3·1		3·03								2·8				3·3					2·9							
127	1980	7	2	14	23	43·27	20·97	8	3·1		2·91			2·9									3·2							2·8					
128	1980	7	13	22	7	44·73	17·31	7	3·4		2·95				3·6																				
129	1980	7	19	0	37	41·45	20·38	12	4·5		4·72	5·5		5·2	4·8				4·3		4·7	4·8	4·4		5·1		4·5	5·5				4·7	4·9		
130	1980	7	31	21	52	43·31	20·95	10	3·2		3·61			3·2									3·5							2·9					
132	1980	9	3	11	59	43·26	29·93	10	3·2		3·29			2·8		3·3			2·9									3·0	3·1	3·2				3·5	
134	1980	10	10	1	3	43·23	20·91	10	2·8		2·85			3·2																					
135	1980	10	11	10	55	43·28	20·95	10	3·0		2·80			3·1																					
136	1980	10	21	19	43	43·23	20·88	10	3·9		3·93	4·1		3·6	3·8	3·0			3·6				4·0					3·6		3·4			4·2		
137	1981	7	24	2	53	44·71	17·27	5	3·0		2·70	3·0			3·0	2·6																			
138	1981	7	24	2	55	44·67	17·24	10	2·9		2·67	2·7			2·8	2·1																			
139	1981	8	13	2	58	44·70	17·22	7	5·4		5·89	5·8		5·3	5·4	5·4	5·4				5·4	5·9	5·8				5·6	5·8							
140	1981	8	13	4	37	44·69	17·19	7	3·5		2·97	3·5		3·5	3·5	3·1	3·7																		
142	1981	8	14	4	44	44·73	17·22	10	3·2		2·95				3·2	2·9	3·3																		
144	1982	7	3	3	41	44·68	17·19	6	2·8		2·66	3·4			2·8	2·5																			
146	1982	10	12	1	33	44·69	17·14	6	3·3		3·20	3·4			3·3																				
147	1983	1	5	4	3	41·96	19·19	10	3·8		4·38	4·1		3·7	3·6	3·4			3·3			3·7	3·9												3·6
148	1983	2	25	18	22	41·95	21·66	6	4·5	6·5	4·29	4·6		4·1		3·9			4·3			4·6	4·4					4·5							
149	1979	9	7	12	57	44·84	17·38	0	3·2	5·0	2·92	4·1	3·4		3·2	3·0				3·8				4·0											3·5
151	1980	11	3	19	11	43·22	20·85	10	3·8		3·68			3·4					3·8				3·9					3·4		3·3					
152	1980	12	8	6	32	43·31	21·03	10	3·3		3·41			3·8														3·3							
153	1980	12	14	2	54	43·27	21·07	10	3·9		4·22	4·5		3·7	4·1	4·0			4·0									3·8	3·9	4·2					
153	1980	12	22	19	9	43·22	20·99	10	3·7		3·93			3·9	4·1	3·0							3·8					3·5	3·3	3·5					
156	1981	3	7	6	53	42·95	20·78	0	3·8		3·70			3·5		3·6							4·0											3·8	
157	1980	5	18	20	2	43·21	20·97	6	5·7	8·0	5·87	6·4	6·3	5·7						6·2	6·2						6·0	5·7				5·8		5·6	
158	1982	7	14	16	14	42·13	21·43	7	4·4	6·0	3·97	4·8				4·0			4·0			3·9	3·8				3·9								
159	1980	5	18	20	26	43·24	20·96	11	5·0		5·07	5·7			4·8				5·0		5·5						5·5				5·3	5·8		5·4	
160	1978	6	20	20	3	40·75	23·26	20	6·0	9·0	5·95	6·8	6·7	5·8											6·5		6·4			6·3					6·6

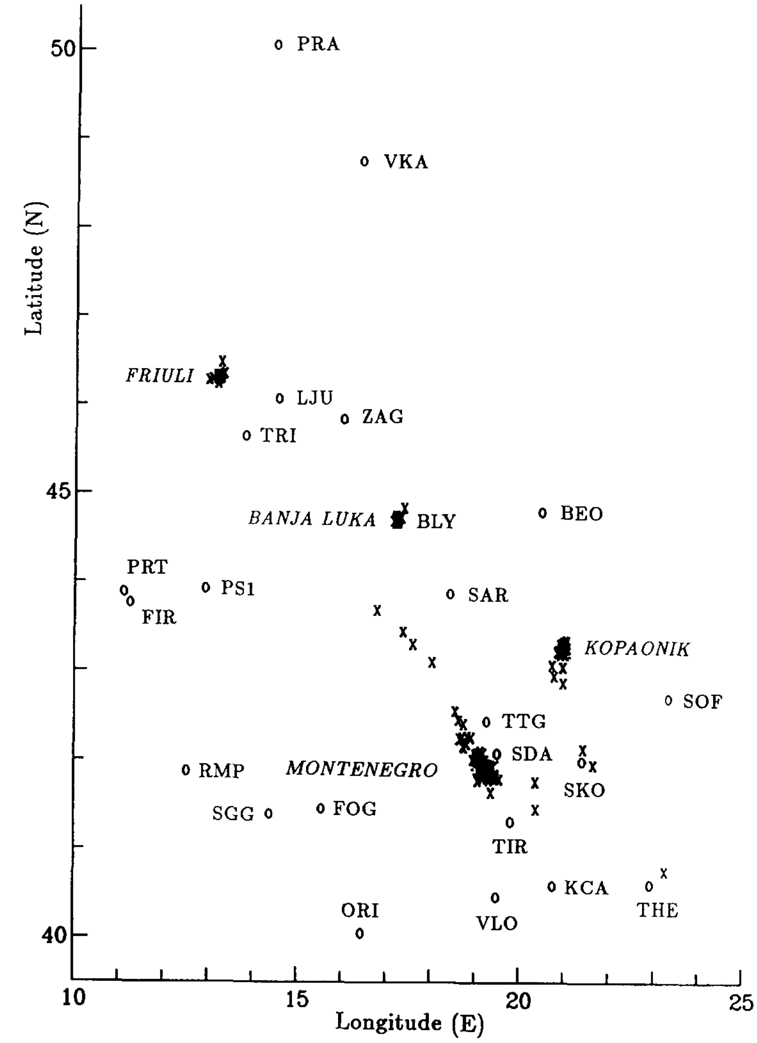

Fig. 1. Geographical relationship of the seismological stations used in this work (PRA, LJU, ZAG, . . .) and the earthquake which contributed strong motion data, mostly from Friuli, Banja, Luka, Kopaonik and Montenegro.

equation of the form

$$M = \log A + \sigma \qquad (2)$$

where A is the peak response on Wood-Anderson seismograph ($T_n = 0{\cdot}8$ sec, fraction of critical damping $\zeta = 0{\cdot}8$ and nominal static magnification $V_s = 2800$). For epicentral distances less than 600 km eqn (2) was used to define the 'local' magnitude M_L and σ is provided in the form of Tables ($\sigma = \log_{10} A_0$) first calibrated for the recordings in Southern California.[4]

Equation (2) and the local magnitude M_L have been used extensively in empirical equations describing peak amplitudes of strong ground motion,[10] Fourier spectrum amplitudes[11] and the response spectrum amplitudes.[12] It was also used to define an extension of M_L, computed from strong motion accelerograph recordings at distances typically less than 100 to 150 km,[5]

$$M_L^{SM} = \log_{10} A_{\text{synthetic}} + \sigma \qquad (3)$$

with

$$\sigma = -\mathscr{A}tt\,(\Delta_0) - b_2\,(M_L^*)(2 - s) - D\,(\bar{M}_L^{SM}) \qquad (4)$$

In eqn (4) $\bar{M}_L^{SM} = M_L^* - b_2\,(M_L^*)\,(2 - s)$, and $M_L^* = \log_{10} A_{\text{synthetic}} - \mathscr{A}tt\,(\Delta_0)$. $A_{\text{synthetic}}$ represents the peak response amplitude (in mm) computed for the Wood-Anderson response characteristics from the recorded strong motion accelerograms. $s = 0$ for recordings on sediments and $s = 2$ for recordings on basement rock.[13] $b_2(M_L^*)$ and $D(\bar{M}_L^{SM})$ (both given in tabular form by Trifunac[5]) correct for the local geologic site conditions at the recording station and for the systematic differences between strong motion (M_L^{SM}) and distant estimates of M ($M = M_L$ for $M \leqslant 6{\cdot}5$ and M_s for $M \geqslant 6{\cdot}5$, where M_s is the surface wave magnitude). $\mathscr{A}tt\,(\Delta_0)$, where $\Delta_0 = (R^2 + H^2)^{1/2}$ (R is epicentral distance and H is focal depth), has been developed,[5] using the frequency dependent attenuation of strong ground motion,[12] for $\Delta_0 < 200$ km and is available in tabular form.[5] Since M_L^{SM} is typically calculated for small Δ_0 (less then 100 to 150 km) and because $D(\bar{M}_L^{SM})$ can be calibrated using locally recorded strong motion data,[14] $\mathscr{A}tt\,(\Delta_0)$ should be insensitive to regional variations provided $H \leqslant 25$ to 30 km.

The main aim of this paper is to propose a procedure for relative calibration of regional empirical attenuation laws (σ in eqns (1) and (2)) and thus to reduce the uncertainties of magnitude estimates for epicentral distances less than about 1000 km. The second aim is to show how by calibrating seismological estimates of magnitude for selected stations surrounding the area of interest, unbiased and more accurate characterization of local strong motion amplitudes can be achieved. During major destructive earthquakes, local seismological instruments usually go off scale and the size of earthquakes must be determined from distant stations. Since errors in magnitude estimate of 0·3 are equivalent to a factor of 2 in ground motion amplitudes (for $M \leqslant 6{\cdot}5$), in the area of strong shaking it is seen that accurate and quick estimates of possible local destruction during several hours following major earthquake may be invaluable in the correct assessment of the scope and of the disaster emergency services and response.

M_L^{SM} is very appropriate magnitude scale for relative calibration of other regional magnitude estimates in hazard analyses in South-Eastern Europe and in many other regions of the world. It is derived from the frequencies near 1 Hz, which are near center of the frequency band used in earthquake engineering, and its definition is intimately connected to many scaling equations of strong ground motion. However, since M_L^{SM} is derived from strong motion data the approach discussed in this paper can be used only when such data is available. We will employ all available strong motion data in Yugoslavia and it will be seen that this data is not properly distributed over the distance and the depth range of interest. Yet, by presenting the current interpretations based on this data, to the extent possible, we should contribute to future expanded use and better appreciation of strong motion recordings everywhere.

Another aim of this paper is to show that relative scaling can be used to test the regional attenuation equations, which are used in the magnitude determinations. In many instances seismological stations adopt magnitude definitions developed elsewhere, but do not have the opportunity to test the consequences of local geologic setting on attenuation along actual wave paths and for actual local station conditions. While many other local magnitude scales can be used for this purpose (using earthquake and explosion sources) M_L^{SM} is of particular interest because: a) it is determined at small epicentral distance (typically less than 50 km and so is less affected by the propagation path effects); and b) it offers possibilities for the most direct calibration of distant magnitudes in terms of strong motion amplitudes and its associated damaging consequences.

DATA

Table 1 and Fig. 1 show the earthquake data and the stations used in this work. The first eleven columns in Table 1 are derived from Table A2 in Jordanovski *et al.*[15] and show the sequence number, year, month, day, hour, minute, latitude (north) longitude (east), focal depth (km), epicentral intensity and M_L^{SM} (Lee *et al.*[14]) respectively, for 122 earthquakes in Yugoslavia and Italy. These earthquakes occurred between 1976 and 1983, mainly in four regions: Friuli, Banja, Luka, Montenegro and Kopaonik (Fig. 1). Columns 12 through 35 present magnitudes reported by the 22 seismological stations considered in this work. Most data in Table 1 has been gathered from various station bulletins which have been accessible at the Geophysical Institute in Zagreb. Unfortunately, not all seismological stations in the area process their data regularly or distribute published catalogues on a timely basis. The future coverage of earthquake activity in this region thus could improve significantly with routine publication and distribution of earthquake bulletins by BEO, SOF, PSI, SGG, FOG and ORI. In other cases small magnitude events or those that occur outside the local area are not processed, thus leading to considerable irregularities in the coverage of earthquake events.

Let us briefly summarize the expressions used at the analyzed stations to compute reported magnitudes. Italian stations TRI and RMP compute magnitude M_{AW} from

$$M_{AW} = \log A - \log A_0 \qquad (5)$$

where A is the maximum horizontal amplitude in mm, and $-\log A_0$ is tabulated versus epicentral distance.[16] Stations FIR, PRT, PS1, FOG, ORI, and SGG compute M_L (local Richter magnitude).

Yugoslav station LJU computes

$$M_{LV} = \log (A/T) - 1{\cdot}52 \log (\mathscr{D}) + 2{\cdot}9 \qquad (6)$$

where A is the maximal amplitude (in nanometers) of S waves or of surface waves, and for $\mathscr{D} < 7°$.

At ZAG magnitude is computed from[17]

$$M_L = \log (A/T) + 2{\cdot}094 \log \mathscr{D} + 2{\cdot}19 \qquad (7)$$

where A is the maximum displacement amplitude in micrometers, and $\mathscr{D}$ is epicentral distance in degrees.

BLY computes magnitude from[18]

$$M = \log A + 1{\cdot}80 \log (T_S - T_P) + 1{\cdot}6 \qquad (8)$$

where A is record amplitude in mm and $T_S - T_P$ represents the difference in arrival times of S and P waves.

At TTG magnitude was computed from

$$M_L = \log (A/T)_{max} + 1{\cdot}4 + 1{\cdot}4\, \mathscr{D}^{1/2} \qquad (9)$$

where A is the maximum trace amplitude (in mm), T corresponds to the period of the wave and $\mathscr{D}$ is the epicentral distance in degrees.

From station SKO we employed three magnitude determinations, M_{Lgh} M_{LV} and M_{LH}, where[19]

$$M_{Lgh} = \log (A/T) + \sigma (\mathscr{D})$$

(SK1 in Table 1 and in all figures). (10)

Table 2. Coefficients a_0 and b_0 and σ_0 in Regression equations $M_L^{SM} - M_{STA} = a_0 + b_0 R \pm \sigma_0$

STA	n	a_0	b_0	σ_0	Range in R (km)
TRI	81	−0·055	−0·00097	0·43	0 to 800
ZAG	50	−0·00076	−0·00028	0·37	200 to 600
TTG	67	0·30	−0·00080	0·40	0 to 800
BLY	70	−0·25	0·00061	0·33	0 to 500
LJU	52	−0·090	0·00037	0·39	200 to 800
SDA	34	0·43	−0·00091	0·38	0 to 200
PRT	42	−0·33	0·000042	0·37	300 to 800
KCA	60	0·42	−0·0012	0·36	100 to 300
PRA	39	−0·12	0·00025	0·41	400 to 1200
SK2	44	0·36	−0·00053	0·36	100 to 900
SK3	68	0·26	−0·00062	0·38	100 to 900
SGG	26	−0·26	0·00012	0·36	300 to 600
VKA	52	−0·46	0·00069	0·36	600 to 800

A is the maximum horizontal component amplitude of Lg wave ($T < 3$ sec.), $\sigma(\mathscr{D})$ is given in tabular form,[20] and

$$M_{LV,LH} = \log(A/T) + 1{\cdot}66 \log \mathscr{D} + 3{\cdot}3$$

($SK2$ for LV and $SK3$ for LH in Table 1 and in all figures)

(11)

Here A represents maximum amplitude of surface waves, and $\mathscr{D}$ is epicentral distance in degrees.[21] Expression (11) is also used at SAR.

Albanian stations, TIR, SDA, VLO and KCA report M_L, the local Richter magnitude calculated from short period seismographs.[22]

For THE our Table 1 lists the surface wave magnitude M_s which can be related to M_L by[23]

$$M_s = 0{\cdot}95\, M_L + 0{\cdot}72 \quad (12)$$

and where M_L is the local Richter magnitude.[24]

The magnitue data for PRA[25] are based on the standard calibrating amplitude curves for European Area.[26,27]

At station VKA (Vienna) the magnitude is determined from[28]

$$M_{LV} = \log(A/T) + 1{\cdot}47 \log \mathscr{D} + 3{\cdot}70 \quad (13)$$

for $3° \leqslant \mathscr{D} \leqslant 180°$ and $3\,\text{sec} \leqslant T \leqslant 27\,\text{sec}$, where A/T is maximum ratio of ground displacement amplitude in μm to the corresponding period in seconds.

DIFFERENCES BETWEEN M_L^{SM} AND $M_{STATION}$

We begin by considering the differences $M_L^{SM} - M_{STATION}$ where 'station' stands for TRI, ZAG, TTG . . . and analyze these difference with respect to the epicentral distance. Figure 2 illustrates these difference for selected eight stations (TRI, ZAG, SAR, TTG, LJU, BLY, SK3, PRT). It is seen that in many instances there are systematic differences which usually increase with epicentral distance. The data are clustered rather than uniformly distributed with respect to the distance, because most earthquakes considered here have occurred in small and well defined zones. These differences can be characterized by

$$M_L^{SM} - M_{STA} = a_0 + b_0 R$$

where R is epicentral distance and a_0 and b_0 can be calculated by regression analysis. Table 2 summarizes a_0 and b_0 for those stations which have adequate number of recordings and for which the differences are spread over sufficiently large interval in R to make simple regression analysis meaningful.

Using data in Fig. 2 and the trends which are described in Table 2 it is possible to modify the amplitude-distance attenuation terms in various definitions of magnitude. These new tentative definitions are summarized in Table 3. Clearly, the suggested modifications in Table 3 must be considered only as tentative and preliminary until more data become available and until other independent tests are carried out to refine these modifications. Our suggested changes in Table 3 show however: (1) how the distance - amplitude attenuation equations can be further improved; and (2) how these improvements can be initiated. Further detailed analysis of large data sets and using multiple station differences should be carried out to provide relative calibration of the stations considered here, as well as for the other seismological stations in this area.

For other stations in Table 1, but not listed in Table 2 averages and standard deviations of $M_L^{SM} - M_{STATION}$ will be presented in the following section.

Table 3. Tentative 'new' definitions for magnitude estimates

STA	New magnitude definition	Applicable distance range (km)
ZAG	$M_L = \log(A/T) + 1{\cdot}921 \log \mathscr{D} + 2{\cdot}19$	200 to 600
TTG	$M_L = \log(A/T)_{max} + 1{\cdot}7 + 1{\cdot}19\, \mathscr{D}^{1/2}$	0 to 800
SKO(SK2)	$M_{LV} = \log(A/T) + 1{\cdot}04 \log \mathscr{D} + 3{\cdot}66$	100 to 900
(SK3)	$M_{LH} = \log(A/T) + 1{\cdot}04 \log \mathscr{D} + 3{\cdot}56$	100 to 900
LJU	$M_{LV} = \log(A/T) + 1{\cdot}32 \log(\mathscr{D}) + 2{\cdot}81$	200 to 800
SDA,KCA	$M_L = \log A - \log A_0 + 0{\cdot}42 - 0{\cdot}001R$	0 to 300
TRI	$M_L = \log A - \log A_0 - 0{\cdot}055 - 0{\cdot}00097R$	0 to 800
VKA	no change required, use equation (13)	300 to 800

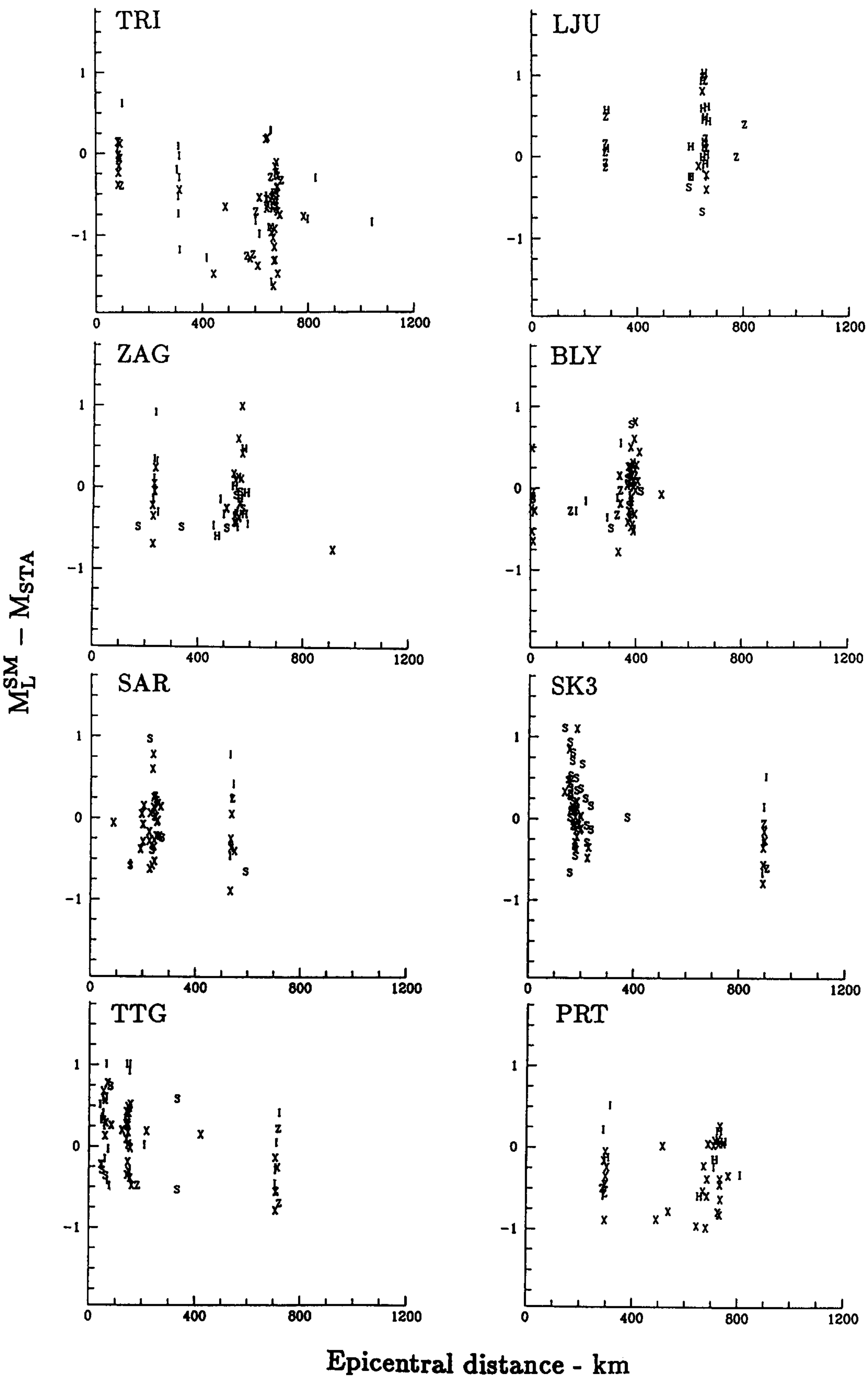

Fig. 2. $M_L^{SM} - M_{STA}$ (where STA represents TRI, ZAG, SAR, . . .) plotted versus epicentral distance (in km). To show possible dependence of $M_L^{SM} - M_{STA}$ on magnitude, different symbols are used as follows: V for $2 \leqslant M < 3$, S for $3 \leqslant M < 4$, X for $4 \leqslant M < 5$, I for $5 \leqslant M < 6$, Z for $6 \leqslant M < 7$, and H for $7 \leqslant M < 8$.

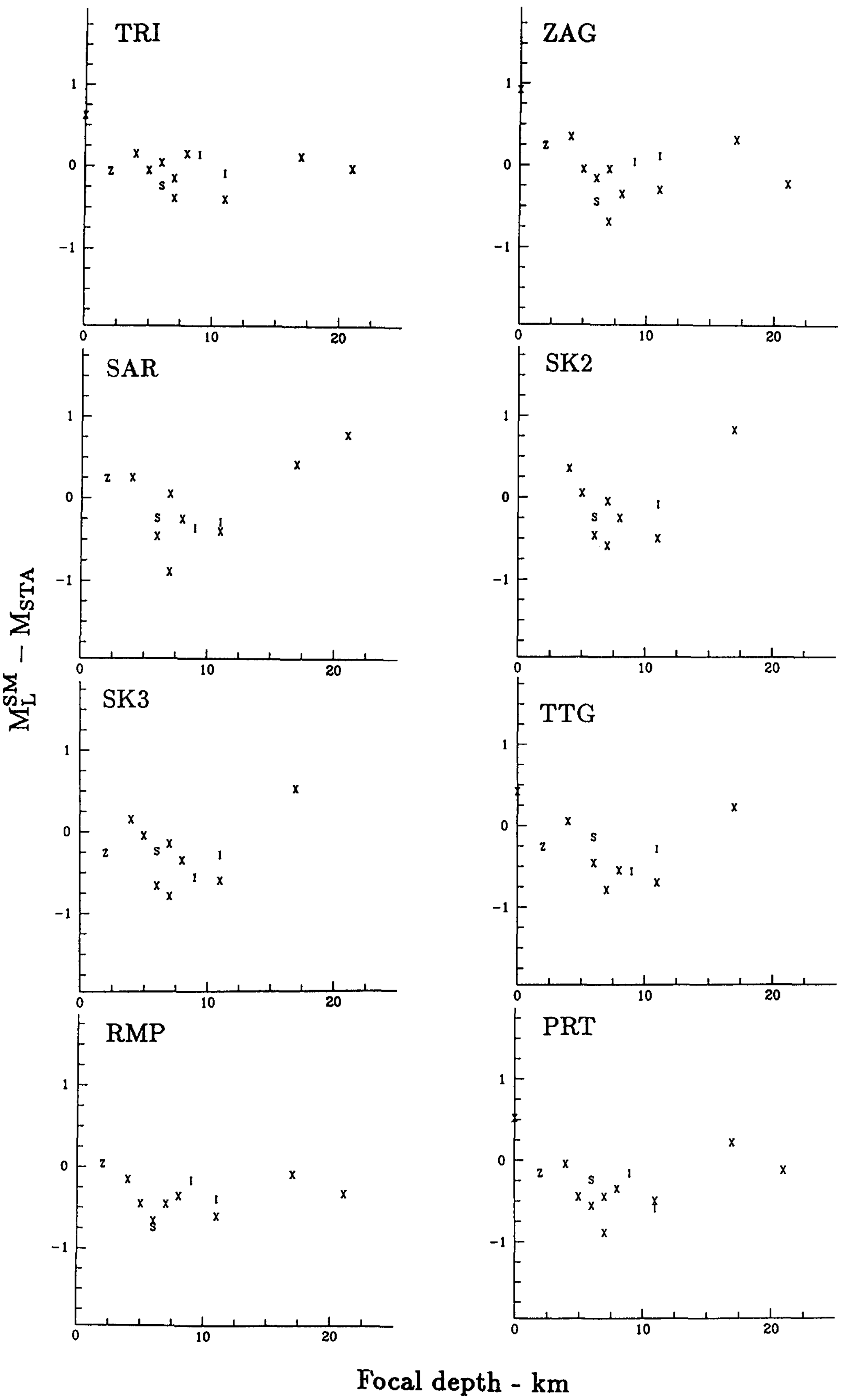

Fig. 3. $M_L^{SM} - M_{STA}$ versus focal depth for earthquakes in FRIULI area (for explanation of symbols used see Fig. 2 caption).

Table 4. FRIULI $M_L^{SM} - M_{STATION}$ versus H

STATION	R(km)	$N(>10)$	AVE	SIG	a	b	σ_H
TRI	87 ± 5	14	−0·01	0·26	0·08	−0.011	0·24
ZAG	231 ± 6	14	−0·02	0·40	0·15	−0·021	0·37
TTG	710 ± 6	11	−0·28	0·39	−0·16	−0·016	0·36
PRT	297 ± 7	14	−0·27	0·36	−0·25	−0·003	0·34
RMP	499 ± 3	12	−0·36	0·24	−0·38	0·003	0·23
PRA	416 ± 4	13	−0·04	0·46	−0·15	0·013	0·44
SK2	895 ± 6	10	−0·10	0·43	−0·48	0·047	0·37
SK3	895 ± 5	12	−0·27	0·37	−0·48	0·026	0·34
SAR	535 ± 5	12	−0·10	0·46	−0·46	0·039	0·39

All changes in Table 3 result in magnitude differences which are less than ·4 magnitude units and in most cases are smaller than typical uncertainty associated with overall magnitude determination process. Yet, these changes and improvements are very important for engineering risk estimates, because systematic over- or under-estimations of magnitudes from the sources contributing to the risk at the site will easily be translated into factors of 2 and 3 in estimated design amplitudes. From engineering viewpoint elimination of biased estimates within a factor of 2 or 3 can be very valuable indeed.

DEPENDENCE OF σ ON FOCAL DEPTH

In eqns (1) and (2) σ should also depend on the focal depth H. Much work has been done to improve and to calibrate σ versus distance $\mathcal{D}$ (measured in degrees) or R (epicentral distance in km).[9,26–30] In contrast very little work appears to have been done on its dependence on focal depth.[31,32]

The amplitude of peak response A usually increases with H, and so $\sigma(H)$ should decrease[4,33] with H. With increasing wave velocities and Q with depth, for shallow foci the energy will be guided horizontally and dispersed and scattered by the near surface inhomogeneities. For deeper sources more down propagating rays will be transmitted (with less attenuation near source) to teleseismic distances, reaching the recording stations with larger amplitudes. The extent to which $\sigma(H)$ will diminish with H will depend on the local velocity gradient and Q structure in the source region.[34]

Most events in the data base summarized in Table 1 have occurred at depths H ranging from 0 to 25 km. Typical errors in determining H are ± 5 km for $M > 4$ and ± 10 km for $M < 4$.

Figures 3 through 5 present examples of the difference $M_L^{SM} - M_{STA}$ plotted versus H. Tables 4 through 7 describe the trends of $M_L^{SM} - M_{STA}$ versus H by

$$M_L^{SM} - M_{STA} = a + bH \pm \sigma_H \tag{14}$$

and also give average (AVE) and standard deviation (SIG) for all measured differences. Tables 4 through 7 also present the average epicentral distance (R – km) and the number (N) of $M_L^{SM} - M_{STA}$ differences for all stations with more than 10 observations. Tables 4 through 7 and Figs 3 through 5 have been arranged to correspond to the seismic source zones: FRIULI, BANJA LUKA, KOPAONIK and MONTENEGRO. $M_L^{SM} - M_{STA}$ has not been plotted for BANJA LUKA because, except for station BLY, $N < 10$.

Analysis of Tables 4 through 7 shows that $M_L^{SM} - M_{STA}$ increases with H (b is usually positive, $\bar{b} = 0{\cdot}011$) only for MONTENEGRO events. The trends b are not significantly different from zero for either FRIULI or for KOPAONIK. For FRIULI all averages of $M_L^{SM} - M_{STA}$ are negative, but this is mainly caused by typically negative $M_L^{SM} - M_{STA}$ versus R (see examples in Fig. 1). Averaging all observed trends of $M_L^{SM} - M_{STA}$ for MONTENEGRO events would give

$$\overline{M_L^{SM} - M_{STA}} = -0{\cdot}13 + 0{\cdot}011\,H \tag{15}$$

This would imply relative $\sigma(H) = -0{\cdot}13 + 0{\cdot}011H$ for this region, for $0 \leqslant H \leqslant 25$ km assuming that M_L^{SM} does not depend on H, which is not likely. Between the depths 0 km and 35 km the average $\bar{b} = 0{\cdot}011$ would imply the difference of 0·28 magnitude units, i.e. decreasing of A by a factor of 2. Since this is opposite to the usual trend[33] of A to increase with increasing depth H, in the other extreme case this would imply that M_L^{SM} increases with H. Such tendency can be explained by Q increasing with depth.

CONCLUSIONS

In this paper we showed how the strong motion magnitude M_L^{SM}, computed from strong motion accelerographs, can be used to calibrate the amplitude-distance attenuation curves for seismological estimates of earthquake magnitude. We found corrections for these attenuation curves to be

Table 5. BANJA LUKA: $M_L^{SM} - M_{STATION}$ versus H

STATION	R(km)	$N(>10)$	AVE	SIG	a	b	σ_H
BLY	9 ± 3	10	−0·19	0·31	−0·23	0·006	0·29

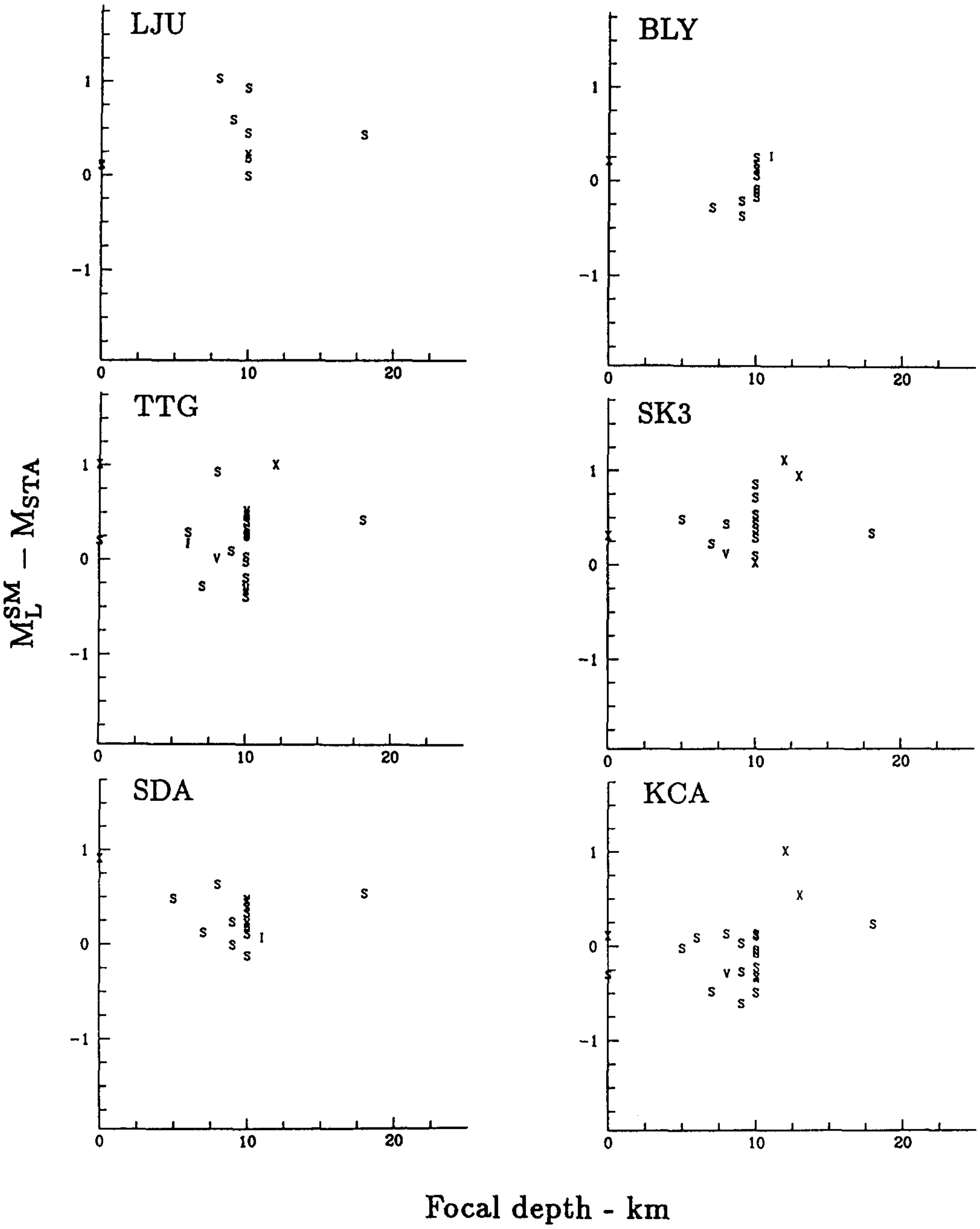

Fig. 4. $M_L^{SM} - M_{STA}$ versus focal depth for earthquakes near KOPAONIK (for explanation of symbols used see Fig. 2 caption).

Table 6. KOPANONIK: $M_L^{SM} - M_{STATION}$ versus H

STATION	R(km)	$N(>10)$	AVE	SIG	a	b	σ_H
TTG	146 ± 7	24	0·24	0·40	0·39	−0·012	0·39
BLY	378 ± 4	13	−0·002	0·22	0·04	−0·004	0·21
LJU	654 ± 6	11	0·45	0·37	0·26	−0·022	0·34
SDA	158 ± 6	17	0·31	0·26	0·54	−0·026	0·23
KCA	293 ± 10	21	−0·05	0·37	−0·29	0·028	0·35
SK1	159 ± 4	20	0·37	0·26	0·32	0·006	0·25
SK3	156 ± 8	17	0·45	0·30	0·25	0·021	0·28
VKA	740 ± 7	13	0·07	0·23	0·011	0·0073	0·22

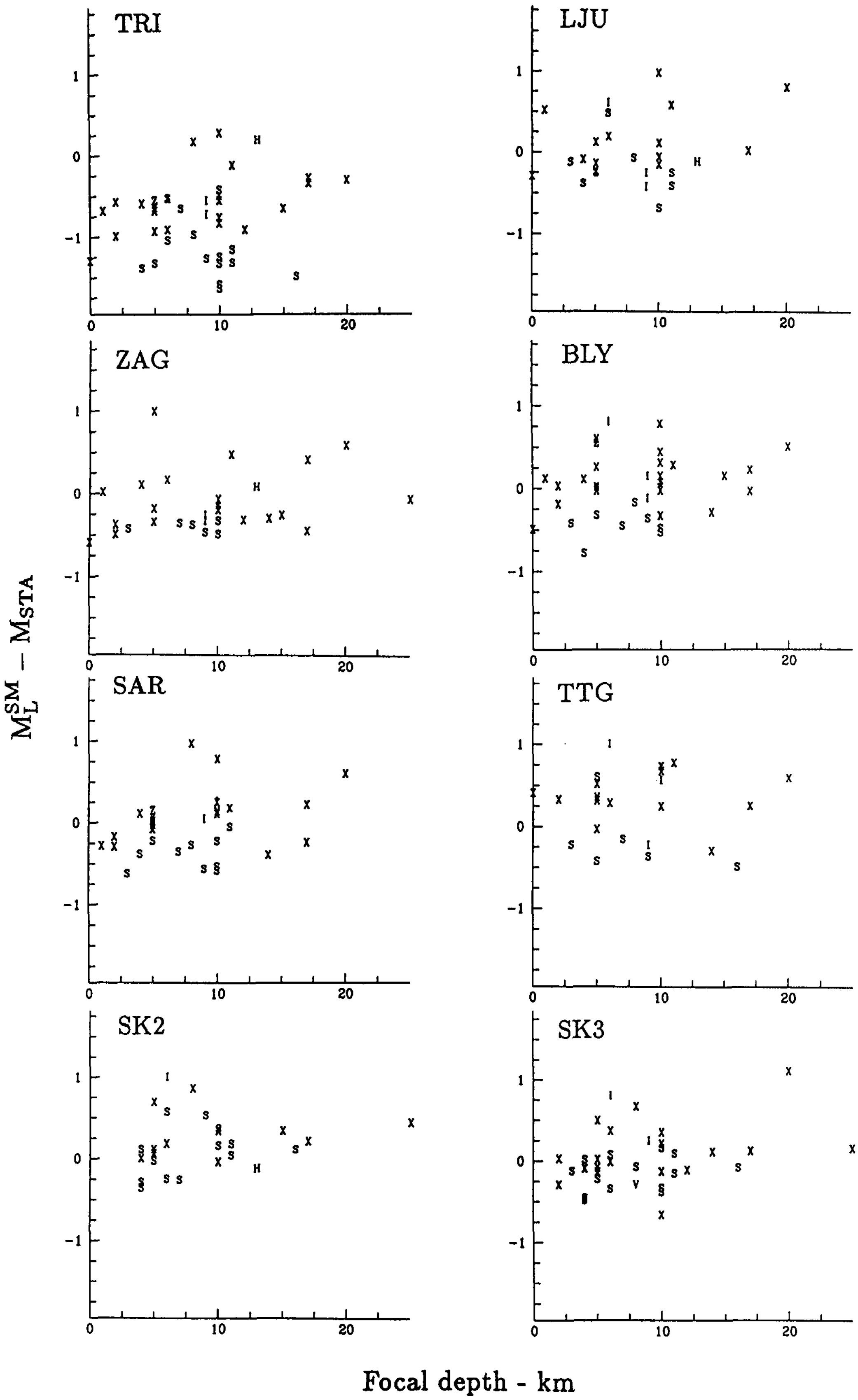

Fig. 5. $M_L^{SM} - M_{STA}$ versus focal depth for earthquakes in MONTENEGRO (for explanation of symbols used see Fig. 2 caption).

Table 7. MONTENEGRO: $M_L^{SM} - M_{STATION}$ versus H

STATION	R(km)	$N(>10)$	AVE	SIG	a	b	σ_H
TRI	653 ± 31	43	−0·76	0·46	−0·91	−0·017	0·45
ZAG	540 ± 31	31	−0·12	0·36	−0·23	−0·012	0·35
TTG	59 ± 11	24	0·24	0·42	0·25	−0·002	0·41
BLY	375 ± 30	37	0·023	0·37	−0·084	0·013	0·36
LJU	639 ± 27	28	0·027	0·40	−0·073	0·013	0·39
SDA	32 ± 15	13	0·41	0·55	0·23	0·024	0·52
PRT	709 ± 31	24	−0·30	0·38	−0·44	0·016	0·36
RMP	519 ± 24	31	−0.30	0·38	−0·41	0·014	0·36
VLO	174 ± 20	31	−0·13	0·40	−0·32	0·024	0·38
KCA	223 ± 24	35	0·21	0·36	0·22	−0·001	0·35
PS1	576 ± 29	26	−0·37	0·41	−0·45	0·009	0·40
THE	384 ± 27	34	−0·30	0·36	−0·35	0·006	0·36
TIR	107 ± 31	43	0·014	0·36	−0.15	0·019	0·34
PRA	1039 ± 28	19	0·23	0·41	0·06	0·024	0·38
SK2	188 ± 23	26	0·20	0·35	0·10	0·11	0·33
SK3	190 ± 19	37	0·01	0·36	−0·16	0·21	0·34
FOG	286 ± 18	14	0·04	0·38	0·018	0·003	0·36
ORI	280 ± 7	15	0·23	0·39	0·56	−0·035	0·35
SGG	387 ± 13	20	−0·22	0·37	−0·36	+0·020	0·35
SAR	234 ± 25	33	−0·04	0·37	−0·19	0·0192	0·35
VKA	787 ± 25	33	0·07	0·41	−0·04	0·0143	0·40

typically smaller than 0·5 magnitude units, and could suggest improved attenuation equations for stations ZAG, TTG, SKO, LJU, SDA, KCA and TRI. With further verification of the proposed changes, it will be possible to estimate M_L^{SM} in epicentral region with improved accuracy. Thus, it will also be possible to better predict the amplitudes of strong earthquake ground shaking near source, and the possible destructive consequences of this shaking, by using distant seismological stations.

For Montenegro earthquakes of 1979, consisting of main event and its aftershocks we found a systematic trend of $M_L^{SM} - M_{STA}$ versus focal depth. This trend could be interpreted by increasing Q with depth,[32,34] but we leave detailed analysis of this phenomenon for further work.

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