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Station Magnitude Bias — Its Determination, Causes, and Effects

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FOR THE COMMANDER

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STATION MAGNITUDE BIAS – ITS DETERMINATION, CAUSES, AND EFFECTS

R. G. NORTH
Group 22

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ABSTRACT

An analysis of some 400,000 station m_b values as reported in the ISC bulletin reveals substantial global variations in station magnitude bias, defined as the mean difference between station m_b and the average m_b of a large network of stations. Although there are clear indications that the biases are functions of both source region and time, they appear to be well correlated with tectonic structure and lateral variations in attenuation characteristics in the upper mantle under the station. Application of these biases as station magnitude corrections reduces the scatter in m_b observations for a single event. Changes in station distribution with time are shown to introduce perceptible temporal changes in the shape of magnitude-frequency curve; these can be greatly reduced by application of the station corrections. These corrections, through their effect on the M_s:m_b diagram and the magnitude-yield relation, are applicable to the problems of seismic discrimination.

TABLE OF CONTENTS

ABSTRACT

I. INTRODUCTION 1

II. MAGNITUDE DATA 3

III. BIAS DETERMINATIONS 9

IV. TEMPORAL VARIATION IN STATION BIAS 15

V. SOURCE REGION VARIATIONS IN BIAS 18

VI. VARIATION OF BIAS WITH MAGNITUDE 22

VII. REGIONAL VARIATIONS IN BIAS 25

VIII. CORRELATION OF BIASES WITH VELOCITY ANOMALIES 37

IX. APPLICATION OF BIASES AS STATION m_b CORRECTIONS 39

X. STATION DISTRIBUTION AND APPARENT CHANGES IN SEISMICITY 44

XI. APPLICATIONS TO SEISMIC DISCRIMINATION 52

XII. CONCLUSIONS 54

ACKNOWLEDGMENTS 55

APPENDIX A 56

REFERENCES 61

STATION MAGNITUDE BIAS - ITS DETERMINATION, CAUSES, AND EFFECTS

I. INTRODUCTION

The existence of large lateral variations in the attenuation of seismic waves has long been recognized. Evidence from the propagation of crustal body wave phases[1,2], the transmission of long period teleseismic P and S waves[3], and surface wave amplitudes[4] has demonstrated the existence of large differences in Q in the upper mantle. These results all indicate that attenuation is highest in the regions of the mid-ocean ridges, concave sides of island arcs, and 'rift' structures such as the western US, and lowest in stable regions such as shields and deep ocean basins. High attenuation further appears to be well correlated with high heat flow and also certain negative velocity anomalies[1,5].

In the present work the effects of these variations in Q upon body-wave magnitude m_b are studied. Substantial station biases have previously been noticed by various authors[5,6]. Bune et al[7] have compared body wave magnitudes given by the USCGS (PDE) and Russian sources, and found that the PDE values were substantially lower. They ascribed this to the regular contribution to the PDE catalog of certain stations in the western US which consistently reported lower magnitudes than most other stations.

The data used here are the station m_b values reported in the Bulletin of the International Seismological Centre (ISC) for the period 1964-73. Station magnitude biases are calculated for over 100 stations and shown to be well correlated with the lateral variations in Q determined by previous authors by other means. These biases are then applied as corrections to station magnitudes and this is shown to achieve a noticeable reduction in the scatter of

m_b measurements for a single event. The existence of such biases is shown to cause detectable differences in the shape of the magnitude-frequency curve, temporal variations in the latter being produced by changes in the set of stations reporting magnitudes. The station corrections obtained are also valuable in the context of seismic discrimination through their effect on the M_s:m_b diagram and also in the determination of magnitude yield relationships.

II. MAGNITUDE DATA

The ISC Bulletin reports values of log (A/T), where A and T are the amplitude and period of the dominant P-wave arrival. Individual station magnitudes can then be computed through

$$m_b = \log (A/T) + f(\Delta,h)$$

where $f(\Delta,h)$ is a factor correcting for the source depth h and the source-receiver separation Δ. The correction of Gutenberg and Richter[8] has been accepted as standard by most seismological organizations, including the NEIS (National Earthquake Information Service) and ISC, for $f(\Delta,h)$. The mean of all reported m_b determinations is then taken as the event magnitude. The ISC bulletin gives an event m_b only when there are at least 3 station m_b reports: the PDE does not impose this restriction.

Evernden[9] found it necessary to adjust the distance-depth correction of Gutenberg and Richter at distances of less than 20°: it seems probable that such adjustments will be highly region-dependent and thus only station reports in the distance range 21-100° have been used here. With this small restriction, the ISC bulletins for 1964-73 contain 404,294 station log (A/T) reports for 59,895 events: of these events 40,353 had more than 3 station log (A/T) reports and were assigned magnitudes by the ISC. The Gutenberg-Richter correction has been applied to calculate station m_b from the values of log (A/T), and only events satisfying the criteria of 3 or more station reports have been used here.

These 40,353 events had 374,981 associated station magnitude reports, contributed by over 500 stations. Many of the latter reported very infrequently and are thus of little use in the bias calculations. Only those stations which reported more than 200 events in any one year (a constraint which requires only that it report ∿5% of seismicity) were selected. There were only 72 such stations; Table I lists the number of m_b observations at each during each year of the period 1964-73. The geographical location of these stations is shown in Figure 1 and given in the appendix. The restriction of m_b reports to these stations reduces the total number of observations used to 307,482 for the data period 1964-73. After the station data set has been reduced to these stations the event magnitudes, defined as the average of all station reports, have been recomputed. The total number of events (still requiring 3 or more observations) is reduced from 40,353 to 38,316. Figure 2 illustrates the frequency-magnitude distribution of the events prior to and after the 72-station restriction: the change in this is clearly small. Surprisingly, most events appear to have been lost at the higher magnitude end of the distribution; the curve for the 72-station magnitudes is however clearly smoother than that for the original data. These larger events which have disappeared may be regarded as somewhat dubious, since no three of our 72 best stations have reported magnitudes for them. Of the 4 events of magnitude 6.7 on the 72-station, 3 or more station reports, event distribution only one is an earthquake; the other 3 are nuclear explosions (Cannikin and 2 in Novaya Zemlya). This may indicate an upper limit to m_b of ∿6.7 for earthquakes.

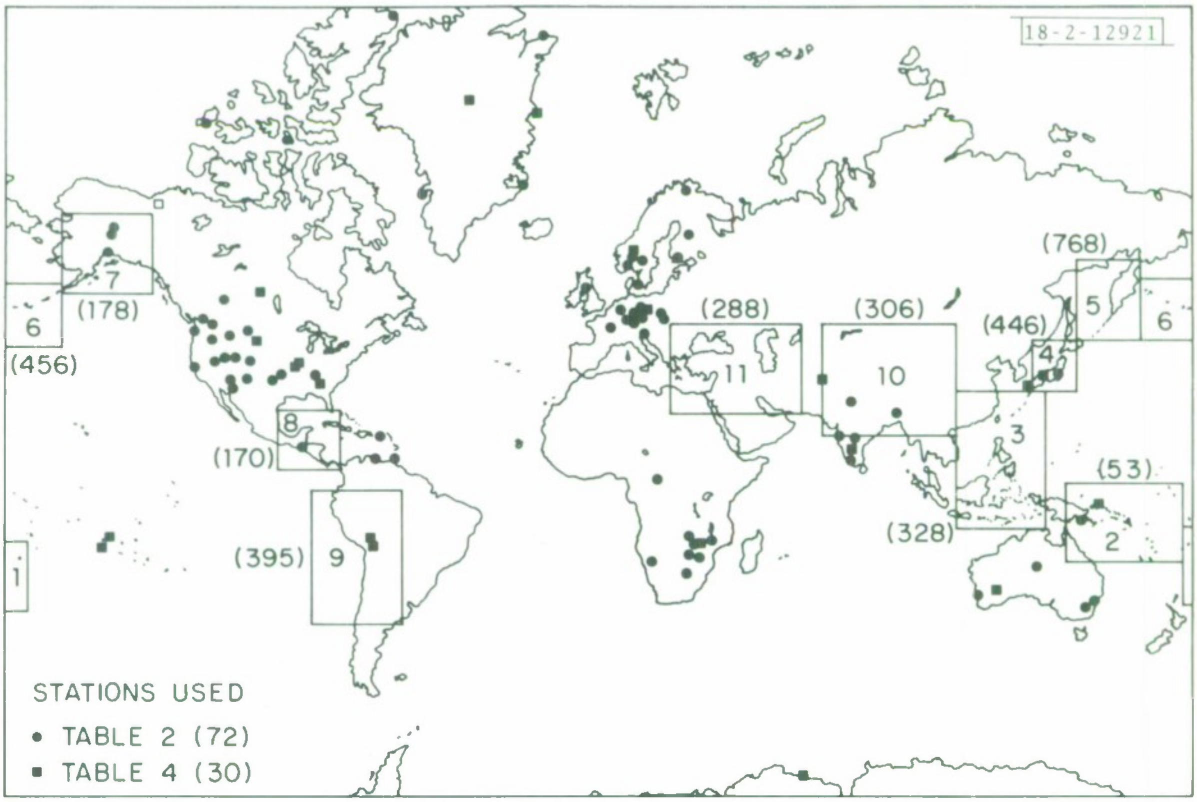

Fig. 1. Location of stations used in this study (Tables II and IV). Also shown are the boundaries of the seismic regions used in section V, with the total number of events in each reported by 15 or more of the 72 stations of Table II.

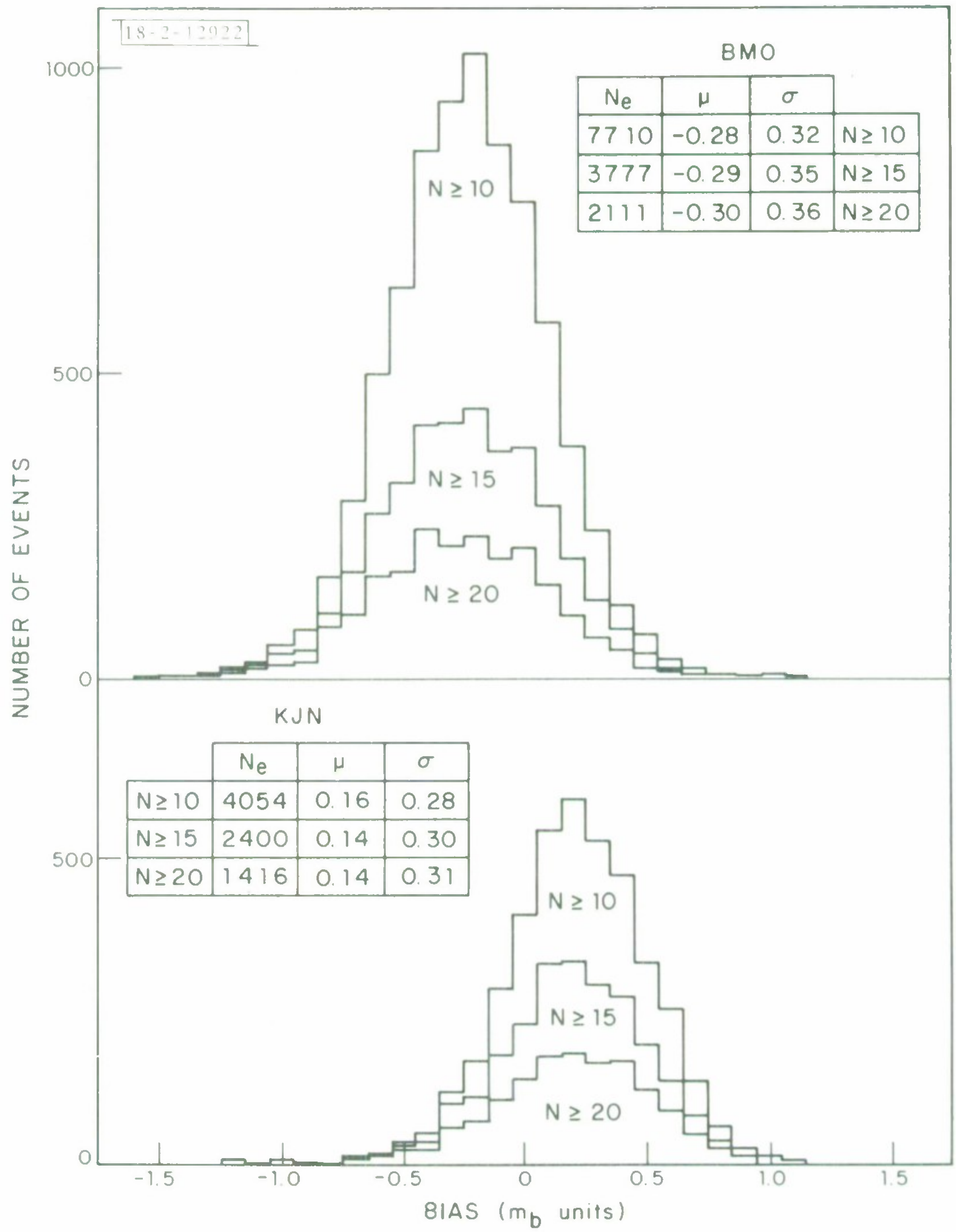

Fig. 2. Histograms of biases for BMO (Oregon) and KJN (Finland) from events reported by 10, 15 and 20 stations, with the number of events N_e, mean μ and standard deviation σ of each distribution.

TABLE I

Yearly numbers of events (reported by 3 or more of 72-station network) reported at each of the 72 stations. Last 4 rows give total of reports by 72 stations, and all stations; and events (requiring 3 or more station m_b reports) for 72-station and all-station networks.

	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973
ALE	0	13	107	100	161	205	288	139	193	184
ALQ	616	429	411	758	866	600	556	290	282	397
ASP	0	0	0	0	0	0	54	575	590	594
BHA	0	73	487	454	487	445	344	272	215	52
BKS	214	186	136	132	195	86	89	129	154	155
BMO	3162	3692	2124	2278	2474	2767	2655	2279	2271	2490
BNG	2	181	417	230	389	387	531	567	564	676
BNS	189	238	145	153	210	272	214	193	149	212
BOZ	640	802	639	520	147	0	0	0	0	0
BUL	0	101	574	555	659	672	639	487	442	664
CAN	411	560	174	210	221	242	260	150	131	103
CAR	49	150	168	112	93	105	186	179	143	140
CIR	0	0	0	0	394	539	465	380	327	518
CLL	251	413	93	1	23	273	322	396	413	541
CLK	0	13	394	300	381	336	341	298	152	236
COL	1095	2054	1170	861	1198	1196	988	1136	904	816
COP	151	136	101	101	166	197	143	133	147	182
CPO	2140	2546	1580	1066	777	789	879	594	453	745
DUG	0	1	1252	1558	1387	523	611	385	377	400
EDM	0	0	0	132	163	172	239	337	304	362
EKA	1050	867	280	270	271	9	0	24	107	216
EUR	1556	2223	1720	1622	1818	1227	1399	1201	1093	1138
FUR	0	0	0	0	354	585	415	404	336	404
GDH	3	159	125	131	126	142	182	207	186	181
GIL	0	0	0	0	410	1324	1202	746	1258	1198
GOL	0	2	103	343	761	667	879	517	475	311
GRF	0	0	0	1	0	409	278	290	235	237
HFS	0	0	0	0	0	367	874	133	0	1543
HYB	0	0	0	0	282	414	366	354	322	368
KEV	616	346	290	318	475	419	285	296	291	342
KHC	326	412	292	273	392	476	377	418	526	600
KJF	0	0	0	0	0	0	0	678	761	698
KJN	857	945	696	751	1096	1001	883	683	28	0
KOD	56	211	310	385	219	321	148	170	255	219
KON	147	304	184	73	168	11	120	85	168	182
KRA	0	0	0	0	235	540	288	147	214	319
KRR	0	0	0	221	583	584	550	363	318	540
KTG	29	151	111	238	190	300	262	264	272	404
LAO	0	0	1454	909	58	1222	1001	794	2106	2658
LJU	291	324	217	201	249	299	198	193	196	333
LON	157	280	283	189	137	125	244	213	249	216
LOR	0	0	0	1	0	0	396	463	406	614
LPS	181	58	114	103	104	134	208	196	147	203
MBC	0	1	265	230	342	407	186	112	168	616
MOX	460	467	299	355	434	535	513	546	506	530

TABLE I (Continued)

	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973
MUN	193	345	246	273	169	117	135	99	108	53
NAO	0	0	0	0	0	0	0	0	1367	2032
NDI	26	205	160	225	264	195	172	138	142	126
NEW	0	0	55	396	370	322	307	263	236	167
NIE	0	0	26	50	154	256	255	218	278	329
NOR	87	99	252	431	541	586	654	454	135	0
NP-	223	39	484	459	575	964	1190	0	0	0
NUR	1131	920	575	591	790	799	739	533	527	651
PMG	474	539	460	456	502	573	377	322	405	327
PMR	0	0	0	161	971	994	1036	995	1024	835
PNT	0	0	0	0	0	42	93	291	294	458
POO	38	654	574	470	271	173	333	187	104	37
PRE	0	65	159	125	101	287	270	315	294	331
PRU	279	314	197	194	302	361	335	281	282	234
RES	0	0	114	144	199	176	152	102	113	435
RIV	144	263	153	166	146	150	177	177	178	176
SHL	176	738	569	454	328	199	127	87	51	24
SJG	35	261	189	182	181	210	242	193	54	80
STU	233	297	227	214	190	132	139	106	107	107
TFO	2867	3816	2402	2394	2551	2476	2040	0	0	0
TRN	120	148	210	145	185	151	114	114	66	104
TSK	0	0	0	332	478	500	373	385	372	322
TUC	474	474	225	255	269	315	345	254	209	213
TUL	0	0	0	0	0	180	480	631	581	948
UBO	3246	4240	2769	2830	2927	2826	968	2048	698	605
WIN	0	11	56	55	25	177	236	220	227	252
WMO	2654	3239	2017	2127	2286	778	0	0	0	0
Total reports 72 sta.	27049	35005	28814	29264	33870	35268	32347	26832	26686	32347
All other stations	2319	4481	5112	8497	8928	7377	7120	5087	9194	10384
Events (72 st)	3916	5051	3755	3794	4023	4045	3595	3065	3232	3840
Events (all st)	3970	5132	3894	4275	4503	4254	3696	3170	3466	3995

* LAO (LASA) was not as bad as it would appear to be for 1968; during this year many m_b reports were assigned by the ISC to individual subarrays (e.g. LF1 etc).

III. BIAS DETERMINATIONS

The bias b_{ij} at the i^{th} station for the j^{th} event is calculated as

$$b_{ij} = m_{ij} - m_j$$

where m_{ij} is the station magnitude and m_j the event magnitude, defined as

$$m_j = \frac{1}{N} \sum_{i=1}^{N} m_{ij} \quad ; N = \text{no. of stations reporting.}$$

Clearly the bias values will only be significant if N is sufficiently large. A suitable test to find the minimum value of $N(N_{min})$ is to increase it until higher values cause no significant change in the shape of the distribution of the biases. Figure 3 shows histograms of magnitude biases for various values of N_{min} for stations BMO (Western U.S.) and KJN (Finland). These, and similar diagrams for many other stations, show that $N_{min} = 15$ is sufficient: larger values reduce the size of the data base with neither significant changes in mean value nor reductions in variance. The restriction that N 15 reduces the number of available events to 4668, with 102,759 associated station m_b reports. Figure 3 shows the distribution of these events with magnitude; none are smaller than m_b 4.5 and 85% are of $m_b \geq 5.0$.

For each of the 72 stations the distribution of biases with respect to event magnitude has been calculated for all events reported $(N \geq 15)$ and the histogram of the biases plotted. Histograms for 9 stations are shown in Figure 4. For all the stations, the normal distribution is a remarkably good approximation to that observed, and thus only the mean and its associated standard deviation are required to characterize the nature of the bias

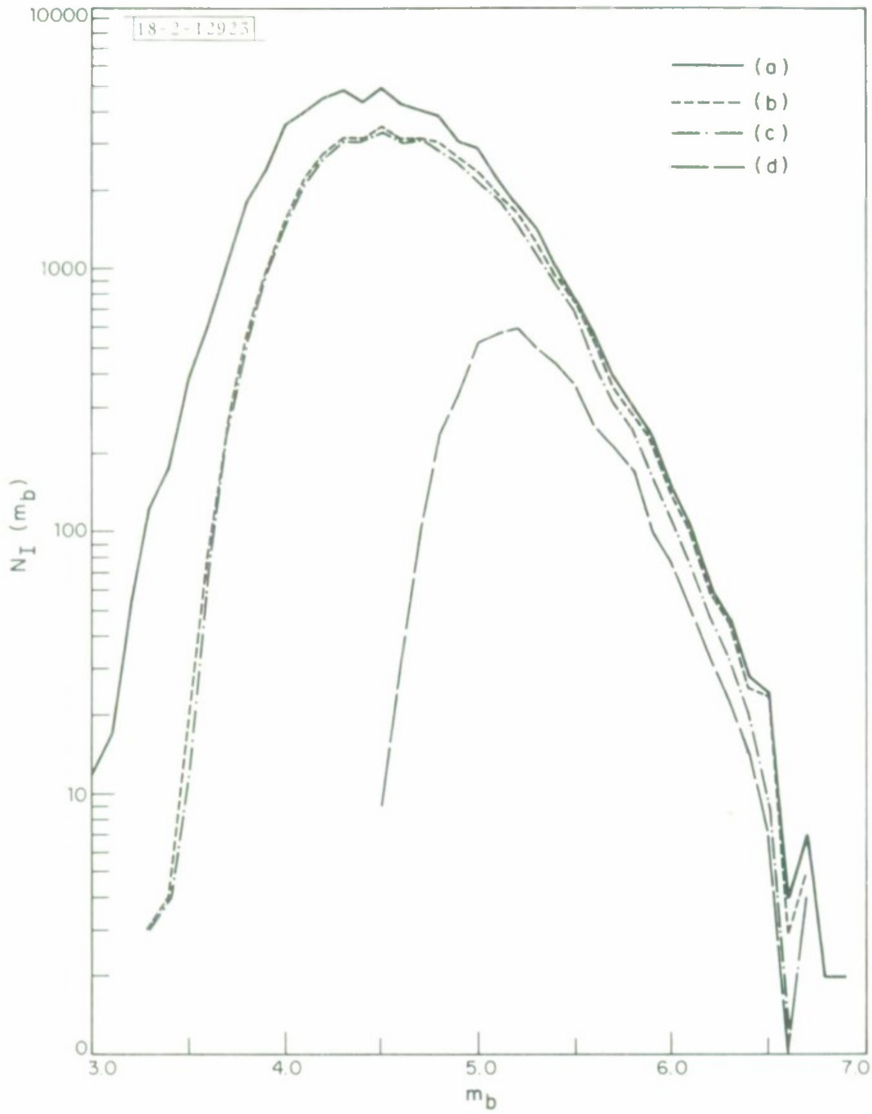

Fig. 3. Incremental magnitude-frequency curves (each point at a given magnitude is number of events of magnitude $m_b \to m_b + 0.1$) for

(a) all events with m_b reported by any station

(b) all events reported by 3 or more stations

(c) all events reported by 3 or more of the 72 stations chosen

(d) all events reported by 15 or more of the 72 stations chosen.

Time period is 1964-73.

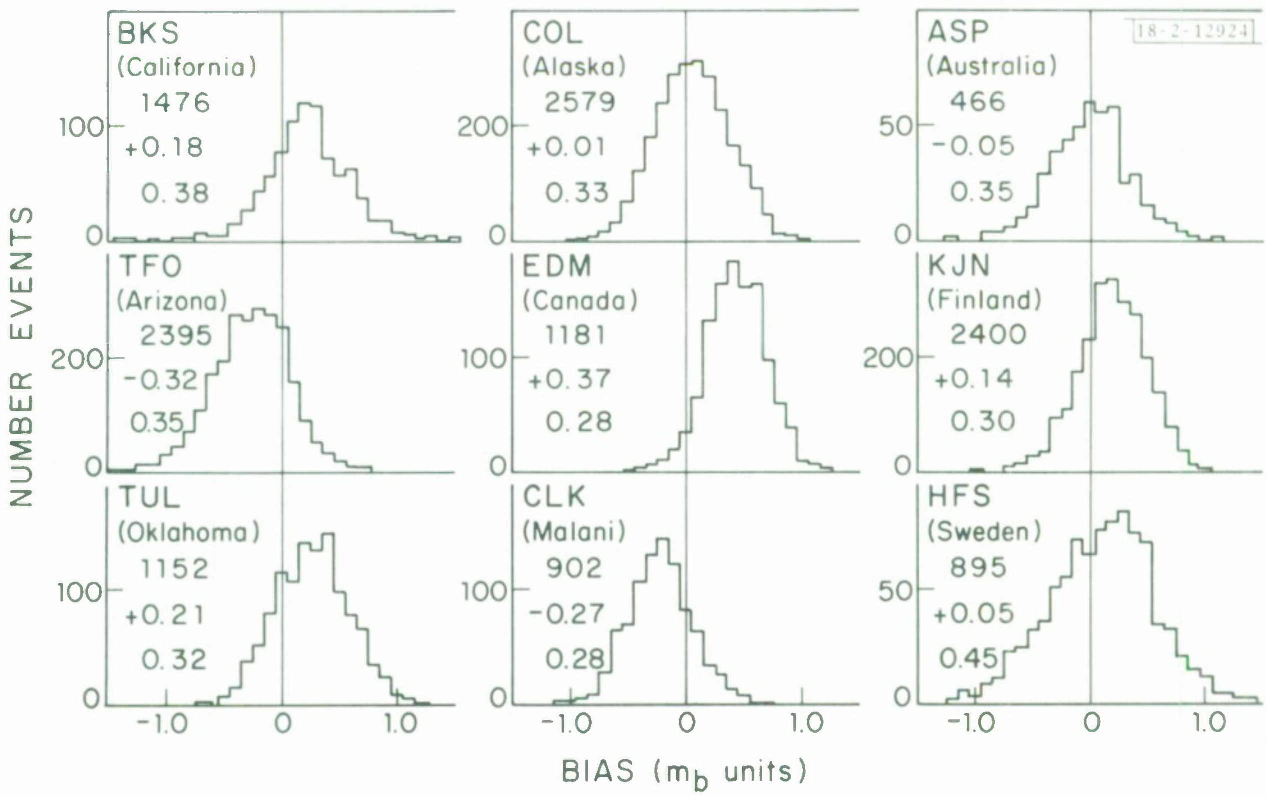

Fig. 4. Histogram of biases for 9 stations, data base 1964-73. Also given are the number of events in the sample and the mean and standard deviation of the distribution.

distribution. Table II gives the number of events reported (requiring $N \geq 15$) at each station and corresponding values of mean bias $\bar{b}$, standard deviation σ_b, and error. The error as given here is the standard deviation of the mean, defined as

$$\frac{1}{\sqrt{N_{15}}} b = \frac{1}{N_{15}} \left[\sum_{j=1}^{N_{15}} (b_j - \bar{b})^2 \right]^{\frac{1}{2}} ,$$

N_{15} being the number of events with more than 15 associated station m_b values reported at the station.

The mean biases calculated can be seen to range from -0.32 to +0.37 m_b units and the standard deviations between 0.24 and 0.50; in only 8 cases (BNG, CAN, EUR, HFS, LAO, TSK, WIN) does it exceed 0.4. The mean itself is well estimated because of the large sample size: the error, a weighting of the standard deviation by the sample size, is a measure of the accuracy of the mean.

Possible causes of these large standard deviations include temporal changes in station bias characteristics, severe dependence upon source region due to extreme lateral variations in either structure or attenuation beneath the station or source, and a possible dependence of bias upon event magnitude through either detection characteristics or changes in reported dominant period, and thus attenuation, through source properties. Each of these factors is discussed below.

TABLE II

Number of events reported at station of 72-station network, requiring 3 or more (N_3) and 15 or more (N_{15}) reports per event. Columns 3, 4, and 5 give mean ($\overline{b}$), standard deviation (σ_b) of distribution of biases for N_{15} events and error (defined in text as $\sigma_b/\sqrt{N_{15}}$) in estimation of mean biases. Last column gives structural type assigned to each station site (S-Shield, P-Platform, R-Rift, O-Oceanic, and F-Foldbelt and Seismic).

	N_3	N_{15}	$\overline{b}$	σ_b	error x 10^2	Structure
ALE	1390	1160	-0.04	0.29	0.85	S
ALQ	5205	1917	-0.20	0.33	0.77	R
ASP	1813	466	-0.05	0.35	1.59	S
BHA	2829	980	-0.28	0.32	1.03	R
BKS	1476	877	+0.18	0.38	1.31	P
BMO	26192	3777	-0.29	0.35	0.56	R
BNG	3944	1029	-0.07	0.50	1.56	P
BNS	1975	1695	+0.20	0.29	0.71	P
BOZ	2748	978	-0.06	0.31	1.00	R
BUL	4793	1368	-0.07	0.29	0.78	R
CAN	2462	507	-0.02	0.40	1.74	F
CAR	1289	674	+0.13	0.38	1.46	F
CIR	2623	938	-0.27	0.30	0.97	R
CLL	2726	1715	+0.20	0.32	0.78	P
CLK	2451	902	-0.27	0.28	0.93	R
COL	11418	2579	+0.01	0.33	0.65	F
COP	1457	1290	+0.36	0.26	0.72	P
CPO	11569	2510	-0.07	0.35	0.70	P
DUG	6117	1753	-0.15	0.35	0.83	R
EDM	1709	1181	+0.37	0.28	0.82	P
EKA	3094	1395	+0.00	0.33	0.89	P
EUR	14997	2913	-0.24	0.40	0.75	R
FUR	2498	1816	+0.10	0.38	0.90	F
GDH	1439	1257	+0.00	0.34	0.97	S
GIL	6138	1842	-0.04	0.35	0.81	F
GOL	4058	1770	-0.28	0.39	0.93	R
GRF	1450	1104	+0.24	0.28	0.85	P
HFS	2917	895	+0.05	0.45	1.50	S
HYB	2106	1166	+0.19	0.37	1.09	S
KEV	3678	2218	+0.02	0.27	0.57	S
KHC	4092	2720	+0.10	0.26	0.50	F
KJF	2137	1036	+0.09	0.28	0.88	S
KJN	6940	2400	+0.14	0.30	0.61	S
KOD	2294	1210	+0.06	0.31	0.88	S
KON	1442	1093	+0.07	0.30	0.91	S
KRA	1743	1251	+0.22	0.29	0.83	P
KRR	3159	1047	-0.24	0.30	0.94	R
KTG	2221	1798	+0.02	0.30	0.71	S
LAO	10202	1705	-0.10	0.47	1.15	P

TABLE II (Continued)

	N_3	N_{15}	$\overline{b}$	σ_b	error x 10^2	Structure
LJU	2501	1739	+0.29	0.30	0.73	F
LON	2093	1333	-0.30	0.37	1.03	R
LOR	1879	1147	+0.06	0.42	1.24	P
LPS	1448	679	+0.04	0.34	1.31	F
MBC	2327	1256	+0.14	0.34	0.97	S
MOX	4645	2762	+0.02	0.27	0.52	P
MUN	1738	397	+0.15	0.37	1.85	S
NAO	3399	755	-0.09	0.29	1.07	S
NDI	1653	906	+0.33	0.37	1.23	S
NEW	2116	1221	+0.05	0.30	0.86	R
NIE	1566	1096	-0.02	0.33	1.00	F
NOR	3693	1986	-0.14	0.33	0.75	S
NP-	3934	1035	-0.00	0.38	1.19	S
NUR	7256	3149	+0.19	0.30	0.54	S
PMG	4435	1146	+0.10	0.38	1.12	F
PMR	6016	2075	-0.08	0.37	0.82	F
PNT	1178	663	+0.13	0.30	1.15	F
POO	2841	1288	+0.17	0.36	1.00	S
PRE	1947	802	-0.07	0.39	1.39	S
PRU	2779	2210	+0.04	0.24	0.51	F
RES	1435	1064	+0.13	0.37	1.16	S
RIV	1730	507	+0.31	0.33	1.50	P
SHL	2753	769	+0.11	0.33	1.22	F
SJG	1547	718	+0.24	0.38	1.40	F
STU	1752	1434	+0.29	0.31	0.81	P
TFO	18546	2395	-0.32	0.35	0.71	R
TRN	1337	704	+0.07	0.35	1.35	F
TSK	2762	1047	-0.07	0.45	1.40	F
TUC	3033	1263	-0.14	0.25	0.71	R
TUL	2820	1152	+0.21	0.32	0.94	P
UBO	23157	2828	-0.11	0.38	0.72	R
WIN	1259	643	-0.09	0.43	1.72	S
WMO	13101	1658	-0.17	0.31	0.76	P

IV. TEMPORAL VARIATION IN STATION BIAS

Bias distributions have been calculated for each individual year of data as well as for the entire time period 1964-73. In general the mean station biases show little variation from year to year, but for some stations, and particularly for some arrays, dramatic changes in the bias distribution took place with time.

Biases for any individual year are calculated only when there are more than 100 observations of events with 15 or more station m_b reports. For 12 stations the largest difference between the mean bias for any one particular year and that for the entire time period 1964-73 exceeded 0.2 m_b units. These stations are in many cases the same as those with large standard deviations of bias distribution as given in Table II. In Figure 5 the change in bias distribution is shown for these 12 stations as a function of date. The dots indicate the mean bias and the bars ± one standard deviation of the distribution. Note that the latter do not indicate errors in the mean; the mean is extremely well estimated because of the large sample sizes (at least 100).

Particularly alarming cases are those of HFS, LAO and EUR. For the first two (arrays in Sweden and Montana) there appears to have been a severe degradation in performance, characterised by large standard deviations, in certain years, and at EUR (Nevada) there is a remarkable decrease in bias over the ten-year time interval. It is difficult to conceive of any rational explanation for the latter: nearby stations DUG and UBO do not exhibit any trend.

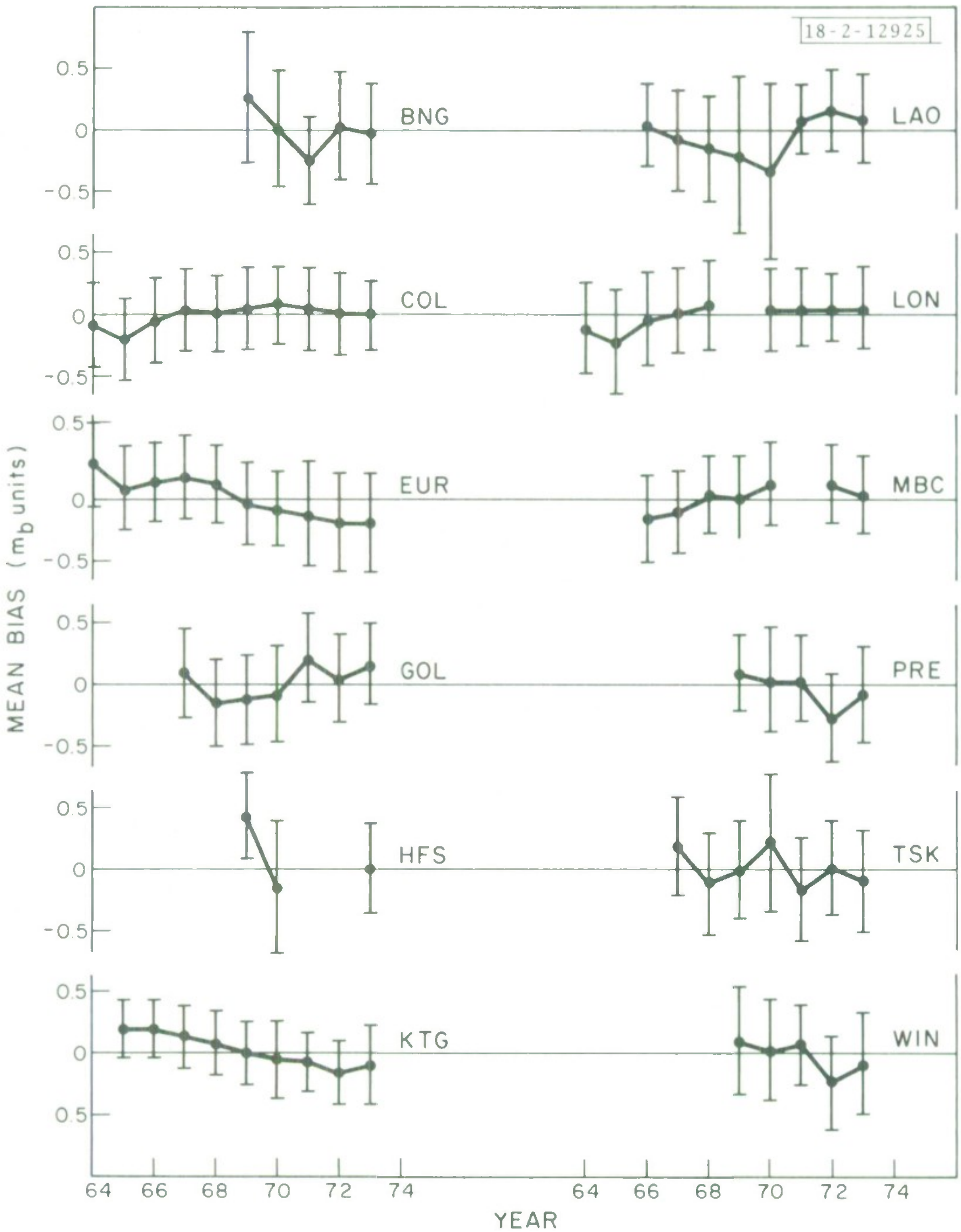

Fig. 5. Annual variations in mean bias for the 12 stations for which the mean in any one year differs from that for the entire time period (1964-73) by more than 0.2 m_b units. The bar denotes ± one standard deviation σ_b of the bias distribution, not the mean.

For stations COL and LON the largest differences from the average bias occur in years 1964 and 65 - during these seismicity was greatly dominated by events in Alaska (64) and the Rat Islands (65); some regional source effects may be operating here. PRE and WIN, both in southern Africa, show a sudden decrease in bias in 1972 - this is not noticeable on similar plots for stations in East Africa.

Most of these temporal changes defy any rational explanation. In general the years with largest deviations of mean bias are also those with the largest variance: thus the statistical significance of these trends may be small. The vast majority of stations used here show no such trends, including those which have reported most events over the entire time interval (e.g., UBO, KJN, TFO).

V. SOURCE REGION VARIATIONS IN BIAS

We may consider the mean station bias $\overline{b}$ as defined in section III to consist of the following factors

$$\overline{b} = b^{s} + b^{cs} + b^{us} + b^{M} + b^{ur} + b^{cr}$$

where b^{cs}, b^{cr} are introduced by crustal structure at the source and receiver respectively, b^{us} and b^{ur} by upper mantle structure in the same regions, b^{M} in the lower mantle part of the ray path, and b^{s} by the source radiation pattern. All of these factors clearly may depend upon the source-receiver configuration through source take-off angle and receiver arrival angle. The Gutenberg-Richter distance-depth correction may be considered to approximate the effects $(b^{cs} + b^{us} + b^{M} + b^{ur} + b^{cr})$ globally; the biases measured then really measure deviations from this average behavior. The term b^{s} accounts for deviations from the average amplitude in a small region surrounding the source due to radiation pattern effects. Station site effects, e.g., seismometer-ground coupling variations due to the medium (hard rock, alluvium) upon which the station is situated, are included in b^{cr}.

Seismic sources, by their very nature, have a tendency to be located in regions of high lateral inhomogeneity, and thus it may be expected that features such as the anomalously high attenuation on the concave side of island arcs[2] can seriously effect m_b determinations. Studies leading to the development of plate tectonic theory have indicated consistency of fault plane solutions and thus presumably radiation patterns over large source regions.

TABLE III

Deviation of mean biases for each source region from mean bias for all regions (column 3, Table II), for sets of contiguous stations in Germany, East Africa, and the western US.

source / receiver	Region 1	2	3	4	5	6	7	8	9	10	11
Germany											
BNS				-0.09	+0.01	+0.02				-0.08	
CLL			-0.04	-0.01	+0.18	-0.04				-0.21	
FUR			+0.21	+0.04	-0.09	-0.15				+0.07	+0.01
GRF				+0.09	0.0					0.0	
MOX			+0.05	-0.04	+0.09	-0.03	+0.25			-0.07	
STU				+0.12	+0.03	-0.13					
East Africa											
BHA			+0.05	+0.10						+0.01	-0.16
CIR			+0.04						+0.15	-0.03	-0.02
CLK			-0.15						+0.07	-0.21	+0.23
KRR			-0.06						+0.10	+0.05	+0.08
Western U.S.											
DUG				-0.08	-0.07	-0.07			+0.18		
EUR	-0.10			-0.08	+0.05	-0.07	+0.07	-0.10	-0.01		
TFO				-0.09	-0.13	-0.06	0.0		+0.15		
TUC					-0.25	+0.02			+0.08		
UBO				-0.13	-0.03	+0.03	+0.05	-0.01	0.0		-0.09

The events used here have been separated into 11 major source regions and biases computed in the same manner as before for events from different source areas recorded at a given station. As in the previous section, 100 or more events are required for determination of mean bias. Variations of bias with source region are generally somewhat higher than those with time given in the previous section. For 16 stations the mean bias determined from events in a given source region differed by more than 0.2 m_b units from that for all sources given in Table II. For many stations there are an insufficient number of events for individual regional variations in biases to be calculated, and thus comparison of biases from a number of regions is severely limited to the better stations. There was no indication that any one particular source region was more anomalous in terms of bias characteristics than any other.

Many of the stations considered here happen to be concentrated in regions which are small in extent compared to source-receiver distances and we may therefore expect to see consistencies in the variations of mean bias with source region. Three particularly small receiver regions are those containing stations in Germany, East Africa, and the Western U.S. Table III gives the variations of bias with source region for each of these area.

It can be seen that, even over these small receiver regions, there is remarkably little consistency in variations of mean bias with source region, the only possible exception being that for events in region 4 (Japan) to the western U.S. Similar tables for other receiver areas such as Scandinavia and India also fail to reveal any correlation of bias with source region. Had we selected smaller source regions it is likely both that regional variations in bias and their consistency across receiver areas would have been more pronounced, particularly in the case of ray paths travelling down descending lithospheric slabs: unfortunately the data base is unsufficient to test this.

This lack of correlation may be taken to indicate that the terms $(b^{cs} + b^{us} + b^{M})$, however large they may be for individual ray paths, tend to average out in such a manner that they cannot be resolved in the present study. It also indicates that the Gutenberg-Richter distance-depth correction is not grossly in error. In particular, much of the observed station bias may be due to the term b^{ur}, and its variation with source region to b^{cr}. This does not of course imply that b^{cs} and b^{us} are not as large as b^{cr} and b^{ur}: in fact the greater lateral heterogeneity in source regions probably means that they will be larger; but they cannot be resolved by the present means.

VI. VARIATION OF BIAS WITH MAGNITUDE

There exist two plausible reasons for expecting a variation of station bias with magnitude. As mentioned in section II, these are the variation of the frequency content of seismically radiated waves with source size, and the station detection characteristics.

All present theories of the seismic source incorporate, in various manners, an increasing proportion of energy at longer periods as the source size increases. This therefore implies that not only the amplitude, but also the dominant period, of the initial P-wave arrival from which m_b is measured, increases with the size of the seismic source. If the attenuation of seismic waves was laterally homogeneous, then its dependence upon frequency could not be detectable by a study of m_b biases, since the average m_b with respect to which we measure biases would depend upon frequency in the same manner. Since attenuation is clearly laterally dependent, as shown by the biases in Table II and the other studies mentioned in the introduction, we may expect a variation of bias with magnitude through the dependence of attenuation as a function of period for average Q in a given region. Unfortunately, we cannot directly measure the variation of bias with period since the ISC Bulletins generally give log (A/T) and not A and T individually. We may, however, be able to detect some variation of bias with event magnitude.

Ringdal[10], Christoffersson et al.[11] and others have considered the effects of station detection thresholds upon magnitude determinations. Their models incorporate, in a complicated manner, the effects of both station biases and detection thresholds upon the relationship between station m_b and 'true'

m_b. The joint estimation of the relevant parameters for each station is an extremely involved procedure. Figure 3 shows the magnitude-frequency distribution of the events used in the bias calculations. Ringdal[10] has estimated the detection capability of the Norwegian seismic array (NORSAR) for events in the Japan-Kuriles-Kamchatka region and finds a 90% detection capability at $m_b = 4.27$. NORSAR is one of the better stations studied here, and it seems certain that 90% detection capabilities for many of the stations will be higher. Figure 3 shows that just over 85% of the events used in the bias calculations have magnitudes ≥ 5.0; this may still be below the 90% detection capability of some stations, particularly since biases are calculated for all stations which report m_b values for 200 or more events annually. Many of the stations in Table I have reported no more than 10% of the total number of events in Figure 3. The percentage of total events reported is however clearly a function of the geographical distribution of seismicity with respect to the station: for example stations in the Western U.S. can observe most of the circumpacific seismicity - those in Europe and Africa are not so fortunate in this respect.

In order to ascertain whether these effects are serious, the data base used has been separated into 3 magnitude classes: $4.5 \leq m_b < 5.0$, $5.0 \leq m_b < 5.5$, and $5.5 \leq m_b < 6.0$. Biases have been calculated for each station for events in each magnitude class, requiring once again 100 or more measurements to determine a mean bias. The variation of mean bias with magnitude is small: in only 13 cases does it exceed 0.1 m_b units and even these are of dubious statistical significance. It may reasonably be assumed that one measure of detection capability is the number of events reported by a particular station, but there appears to be no significant correlation between this and the variation of mean bias with magnitude.

The restriction of bias calculation to events with 15 or more station reports requires that the sources used are of fairly large size and at this level we may be above the detection thresholds of most stations. The effects of such thresholds is probably serious at smaller magnitudes, for which the biases obtained may not be valid: the only measure of this is whether application of the biases at these levels reduces the scatter in magnitude observations and thus the variance in average magnitude. This will be examined in a later section.

VII. REGIONAL VARIATIONS IN BIAS

In the previous three sections the dependence of station magnitude bias upon time, source region, and magnitude has been examined. In some cases the variation of mean bias with time has been shown to be associated with large variances of the distribution, and the effects of magnitude variations appear to be small. It has been tentatively concluded in section V that the mean biases obtained do represent the effects of attenuation in the region near the receiver. In this section we examine the correlation between these biases and other indications of lateral variations in attenuation.

Figures 6 through 12 indicate the variations in mean bias (hereafter referred to as station bias) across North America, Europe, Africa, Australia, and India. In the continental U.S. (Figure 7) the large differences in attenuation between the western and eastern U.S., previously noted by Romney et al.[1], Solomon and Toksoz[3] and Solomon[4], are clearly apparent. Attenuation is obviously higher in the western U.S. than in the older stable regions of the east.

Unfortunately our original data base of 72 stations contains only 3 in the eastern U.S.A., and to improve this situation biases have been calculated for 30 further stations including some in this area. These stations do not satisfy the criteria (viz at least 200 reports/year) of section II; however each reported at least 500 observations over the time interval 1964-73. Because of the paucity of data, we are unable to determine any temporal or source region variations in these biases, and they must necessarily be considered less reliable. Table IV lists these stations, the number of

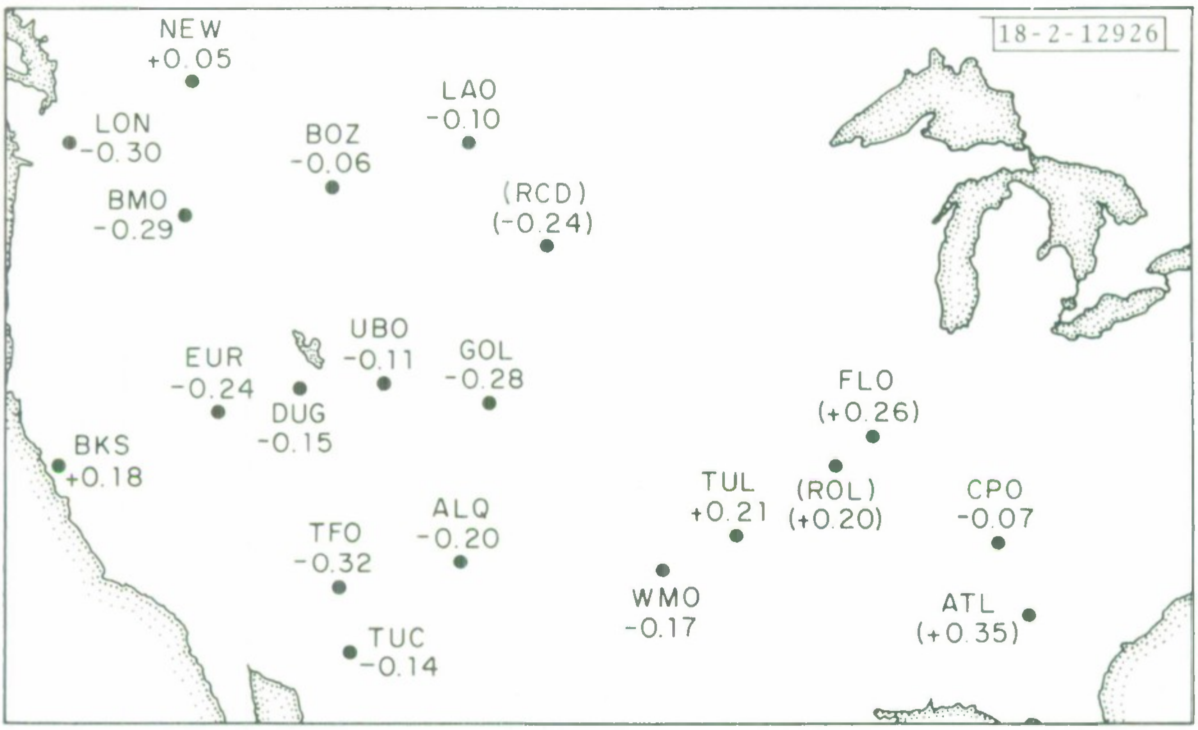

Fig. 6. Mean biases for stations in the continental USA. Values in parentheses are from Table IV; all others are from Table II.

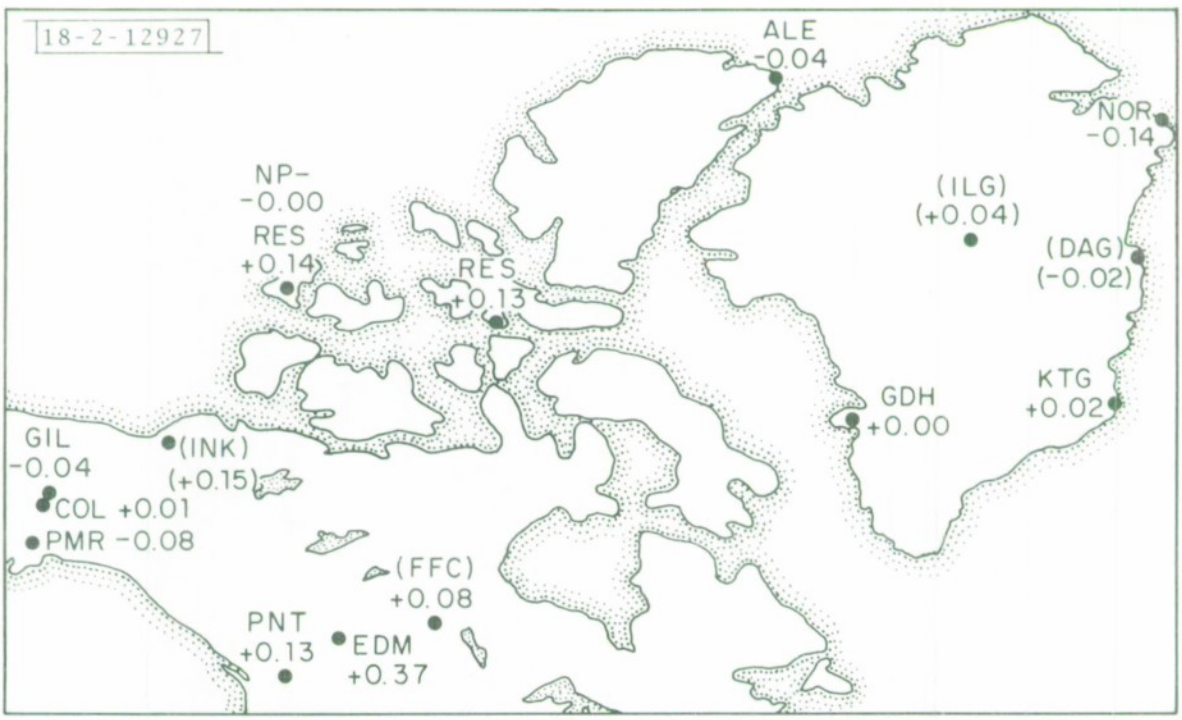

Fig. 7. Mean biases for stations in Canada, Alaska, and Greenland. Values in parentheses are from Table IV; all others are from Table II.

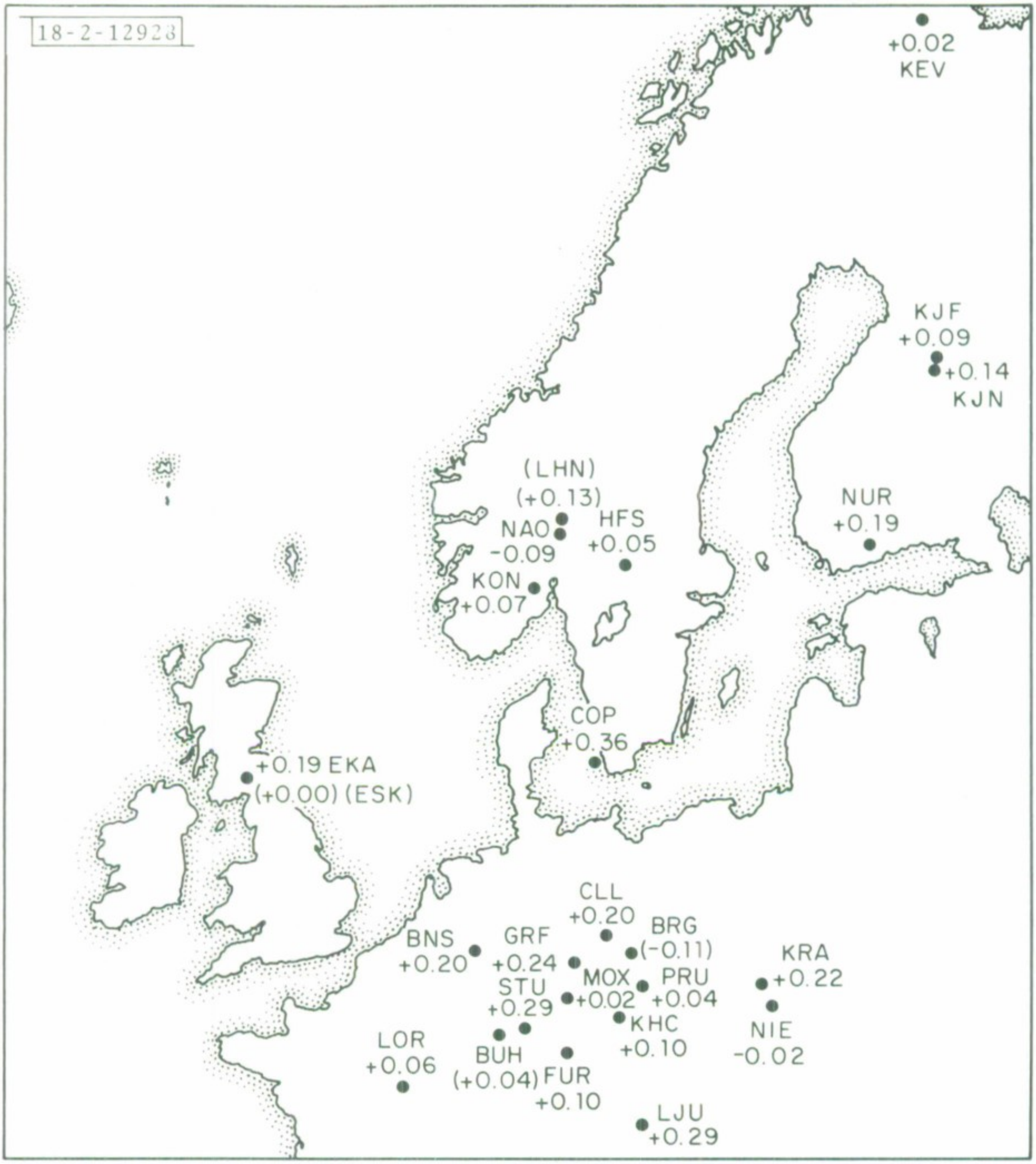

Fig. 8. Mean biases for stations in Europe. Values in parentheses are from Table IV; all others are from Table II.

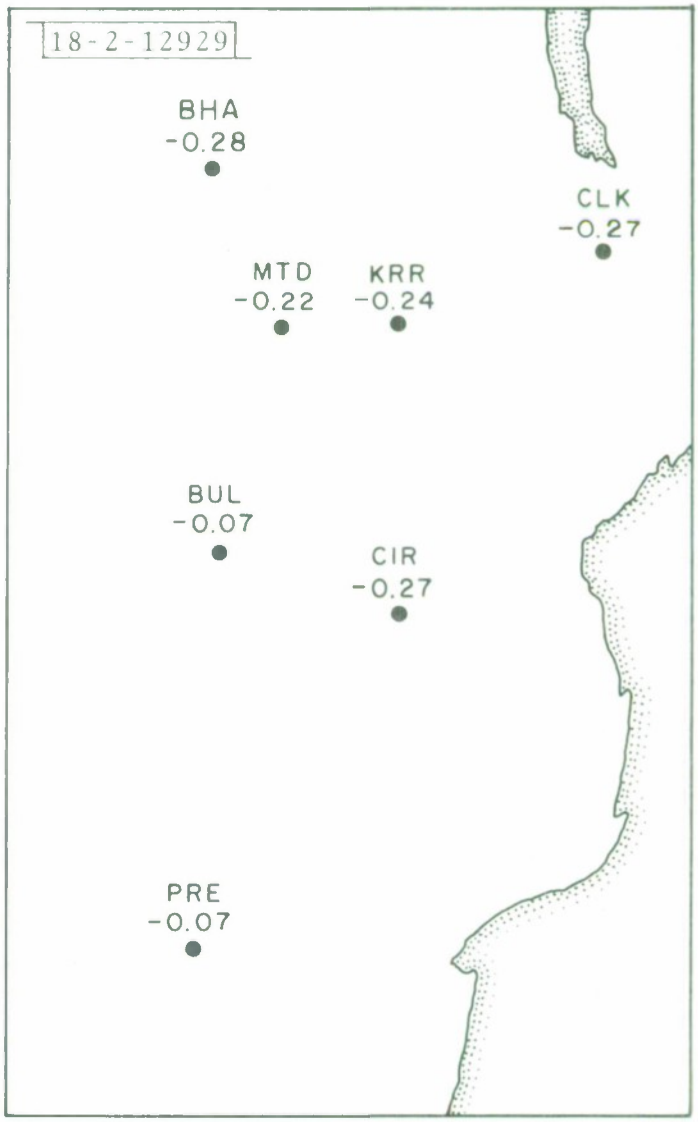

Fig. 9. Mean biases for stations in East Africa. Values in parentheses are from Table IV; all others are from Table II.

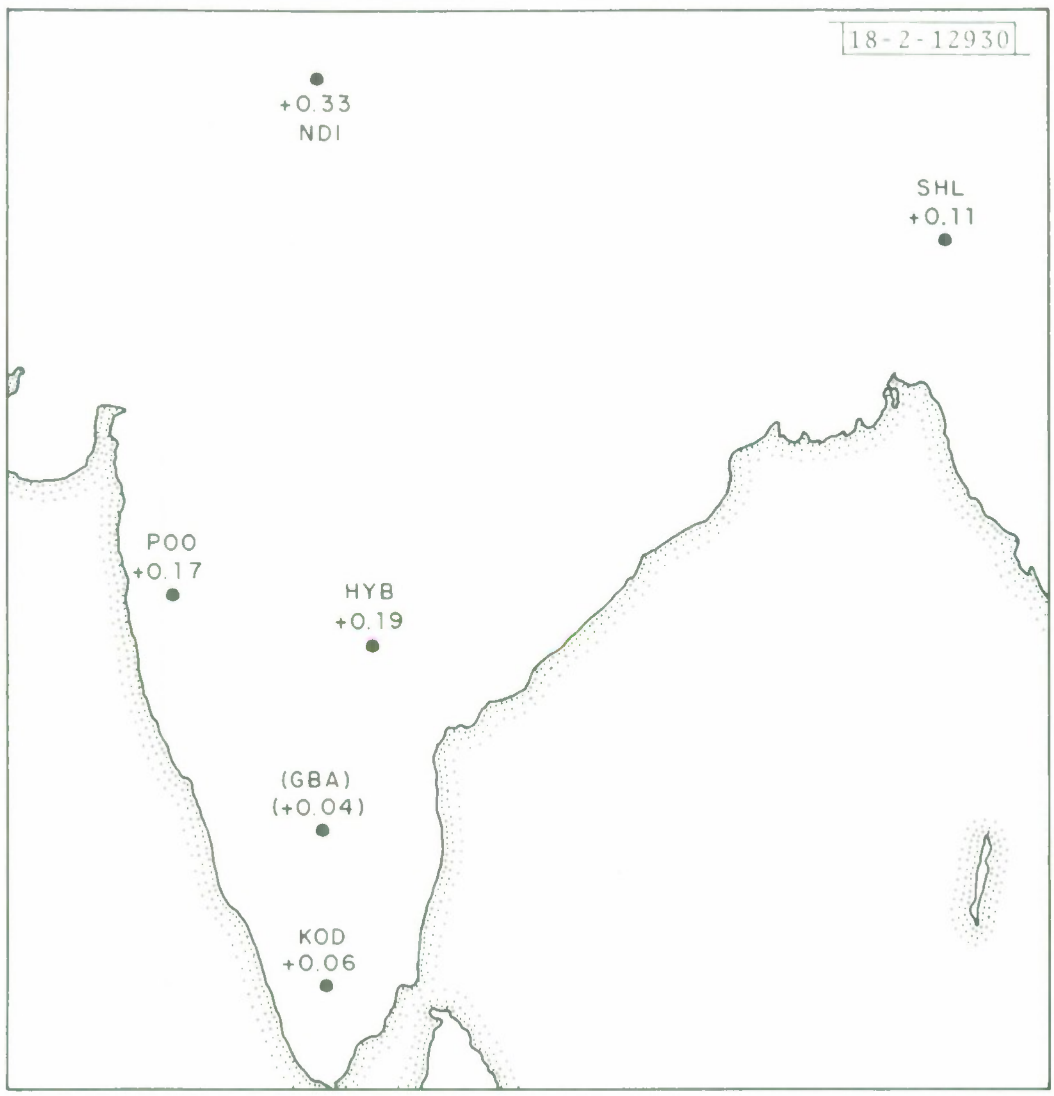

Fig. 10. Mean biases for stations in India. Values in parentheses are from Table IV; all others are from Table II.

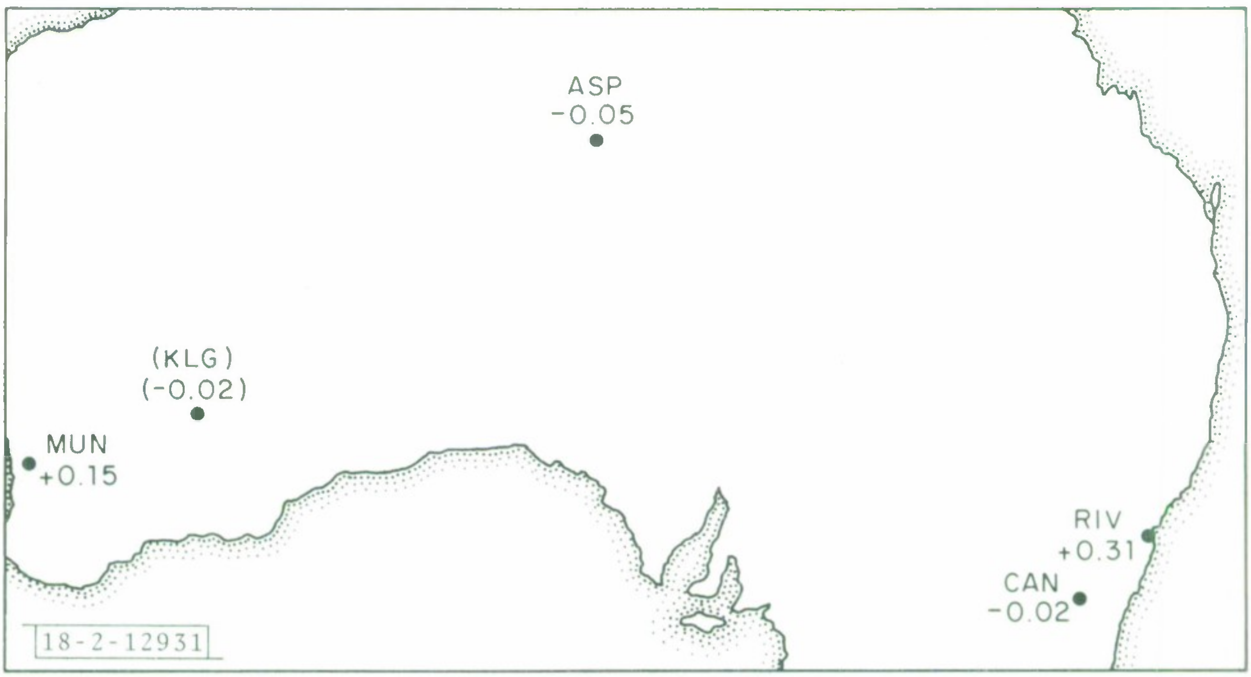

Fig. 11. Mean biases for stations in Australia. Values in parentheses are from Table IV; all others are from Table II.

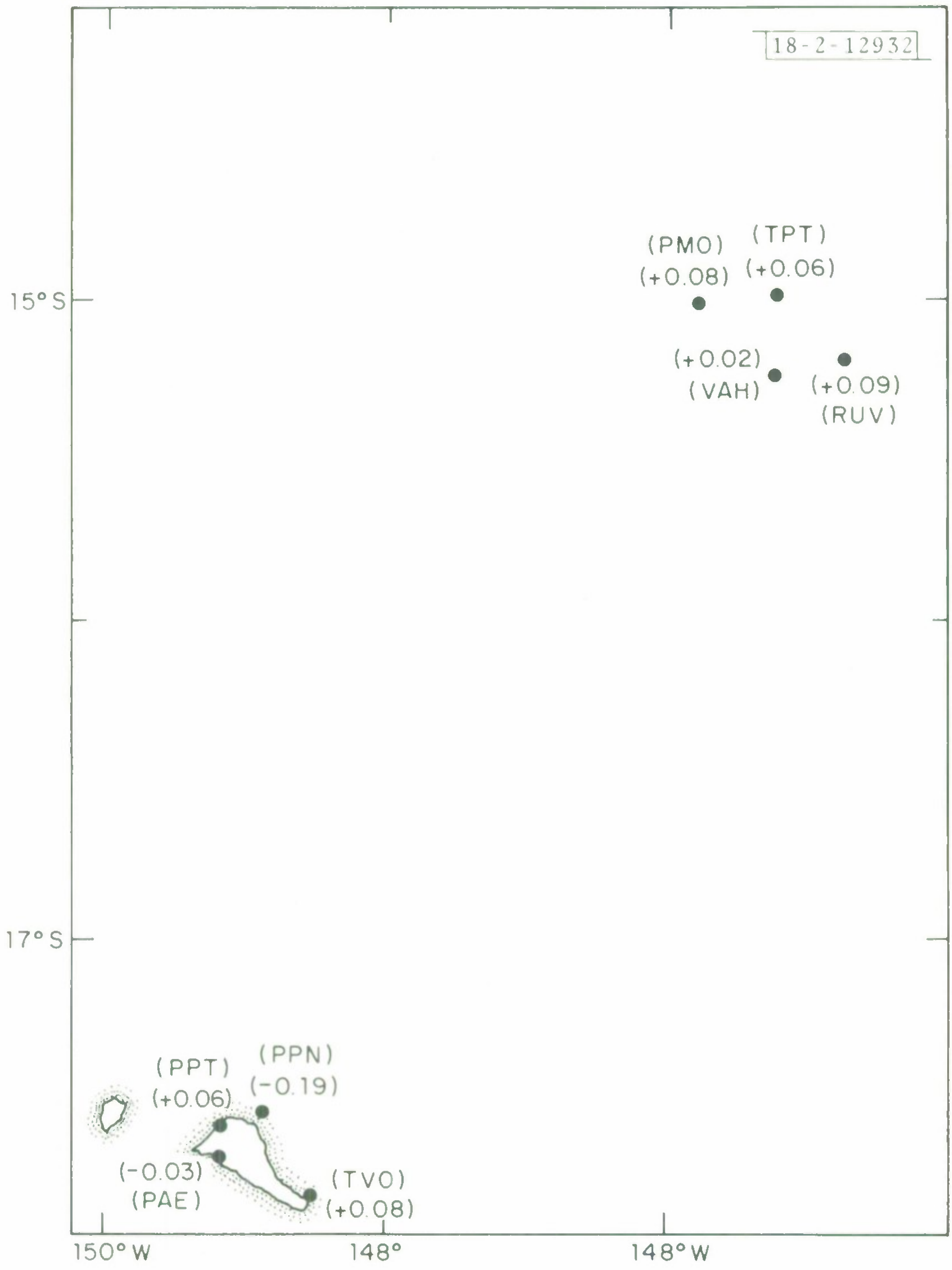

Fig. 12. Mean biases for stations in French Polynesia. Large island at lower left is Tahiti. Values in parentheses are from Table IV; all others are from Table II.

TABLE IV

Number of events (assigned m_b values by 15 or more stations) reported by 30 supplementary stations. Next columns give mean and standard deviation of bias distribution for these events, error, and structural type (for definitions of last two see caption to Table II).

	N(15)	$\bar{b}$	σ_b	error x 10^2	Structure
ABU	702	+0.29	0.53	2.04	F
ATL	213	+0.35	0.51	3.40	P
BRG	749	-0.11	0.26	0.96	F
BUH	414	-0.04	0.38	1.90	F
DAG	394	-0.02	0.27	1.35	F
ESK	650	+0.19	0.37	1.42	P
FFC	568	+0.08	0.29	1.21	S
FLO	495	+0.26	0.31	1.41	P
GBA	350	+0.04	0.37	1.95	S
ILG	314	+0.04	0.42	2.47	S
INK	904	+0.15	0.29	0.97	S
KBL	578	+0.09	0.31	1.29	F
KLG	639	-0.02	0.45	1.80	S
LHN	476	+0.13	0.36	1.64	S
LPB	455	+0.07	0.31	1.48	F
MAW	190	+0.11	0.35	2.50	S
MTD	432	-0.22	0.30	1.43	R
OIS	392	-0.08	0.41	2.13	F
PAE	248	-0.03	0.29	1.81	O
PMO	277	+0.08	0.35	2.06	O
PNS	370	-0.08	0.45	2.37	F
PPN	233	-0.19	0.32	2.13	O
PPT	237	+0.06	0.29	1.93	O
RAB	766	+0.12	0.43	1.54	F
RCD	264	+0.24	0.31	1.94	P
ROL	392	+0.19	0.31	1.55	P
RUV	227	+0.09	0.37	2.46	O
TPT	299	+0.06	0.34	2.00	O
TVO	235	+0.08	0.28	1.87	O
VAH	283	+0.02	0.32	1.88	O

observations of events with at least 15 associated m_b reports given by each, and the corresponding mean, standard deviation and error. Biases for these stations are included in Figures 7 through 12; they are given in parentheses.

Inclusion of stations ATL, FLO, RCD and ROL further clarifies the differences in attenuation in the U.S. We have only one station in California (BKS); its positive station bias does agree, however, with a decrease in attenuation near the west coast noted by other authors. Differences in station bias of up to 0.6 m_b units are apparent in the U.S.

An examination of Figures 7 through 12 confirms that station biases are highest, and thus attenuation lowest, in shield regions such as Canada, India, Scandinavia and Australia. The only region where biases as low as those in the western U.S. are observed is East Africa (Figure 9): the effect of the East African rift valley is apparent and surface wave dispersion studies[12,13] have shown clear similarities in velocity structure between these two regions.

We have 8 stations in an oceanic region: these are all located in the small area in French Polynesia shown in Figure 12. Seven of these stations have mean biases in the range -.03 to +.09 m_b units. Other small regions shown in Figures 6 through 11 also show a consistency in mean bias (Rhodesia, Figure 9; Northern Germany and Finland, both Figure 8).

Each station in Tables II and IV has been assigned to one of 5 tectonic structures: shield, aseismic platform, rift, oceanic, and foldbelt (including present seismic regions). These are denoted by S, P, R, O, and F respectively in Tables II and IV. Figure 13 shows histograms of mean station bias for each region. The distinction between rift structure and all the other types is

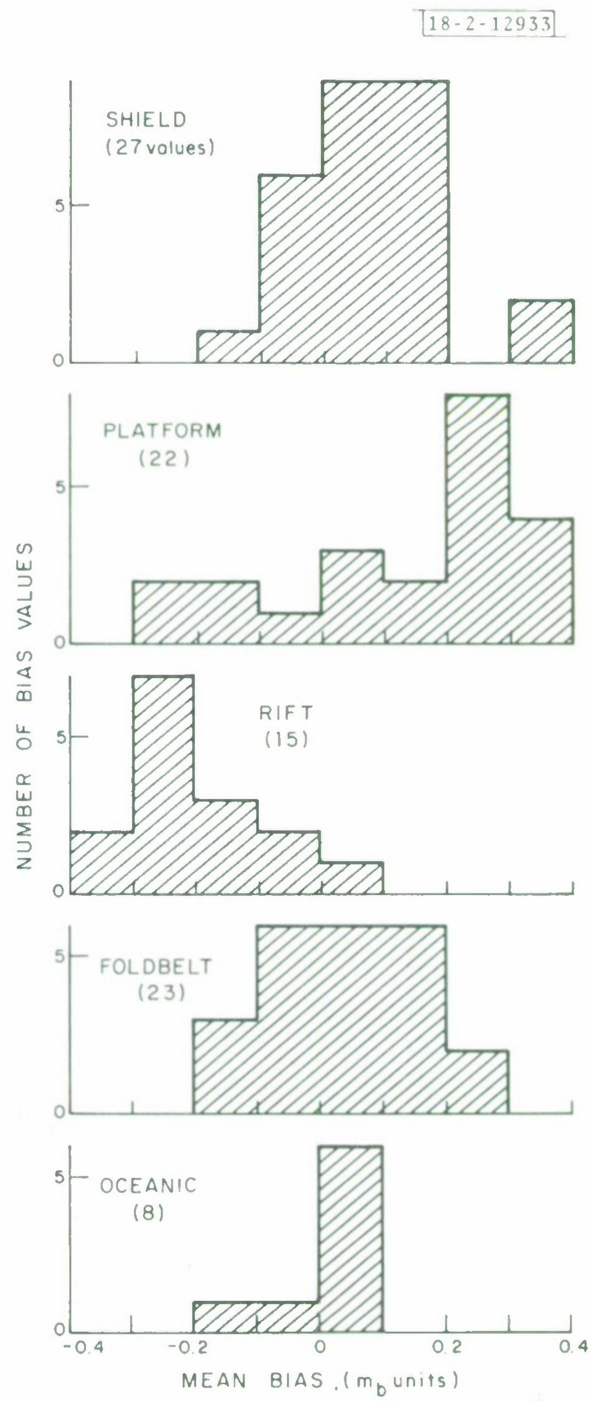

Fig. 13. Mean biases separated into sub-station structure classes: structure types from Tables II and IV.

clear; that between shield, platform, foldbelt and oceanic is not so obvious. The sharp peak in the oceanic biases is certainly not representative; all these biases are from a very small region in the South Pacific (see Figure 12). Biases in platform regions are slightly higher than in shield: this is not too consistent with other measurements of attenuation for these two structural types. In seismic regions, particularly on the concave side of island arcs, Molnar and Oliver[2] have postulated high attenuation on the basis of S_n propagation characteristics; the histogram of mean biases for stations in seismic regions (mainly from Japan, South America, Alaska and the Caribbean) is not consistent with this. A comparison of the geographical distribution of seismic activity with that of these stations reveals that the region directly behind and above the descending lithosphere in their vicinity is poorly sampled by teleseismic ray paths: this may be a contributing factor to these unexpectedly high (or, more precisely, non-low) values of station bias.

Despite all these reservations, the correlation between tectonic type and bias shown here is sufficiently good that our earlier conclusion that the biases as measured reflect upper mantle conditions near the receiver would appear to be justified. The agreement shown is not unexpected in view of previous studies, as mentioned in the introduction; it is however gratifying that such a poor measure of amplitude as m_b can reveal some of these differences in attenuation.

VIII. CORRELATION OF BIASES WITH VELOCITY ANOMALIES

An association of regions of high attenuation with negative velocity anomalies has been remarked by many previous authors[1,5,14]. Surface wave phase velocities, as summarised by Knopoff[15] are highest in shield and aseismic platform regions and lowest in rift and foldbelt areas, these being correlated with high and lower upper mantle velocities respectively. Marshall[16] has measured biases for many of the stations used here: these agree substantially with those given in Table II. He has demonstrated a relation between station bias (and thus attenuation) and P_n velocities beneath the station for the continental U.S., and assumed this relation to hold elsewhere in the world. Figure 14a shows magnitude biases measured for stations within the U.S. versus P_n velocities beneath the stations. The P_n values used here are from the map of Herrin[17]. There is no doubt that bias increases with increasing P_n, though there are some anomalies (particularly WMO, about which more is said in section X). Marshall[16] has applied the P_n-bias relation he derives to improve the magnitude-yield curve for explosions and demonstrated that the use of both receiver and source biases can dramatically improve the linearity of this curve. Figure 14b shows biases versus P travel-time station anomalies for the U.S., from Figure 20a of Hales and Herrin[18]. Here again the correlation is almost convincing, if we ignore CPO and WMO (for possible justification see section X).

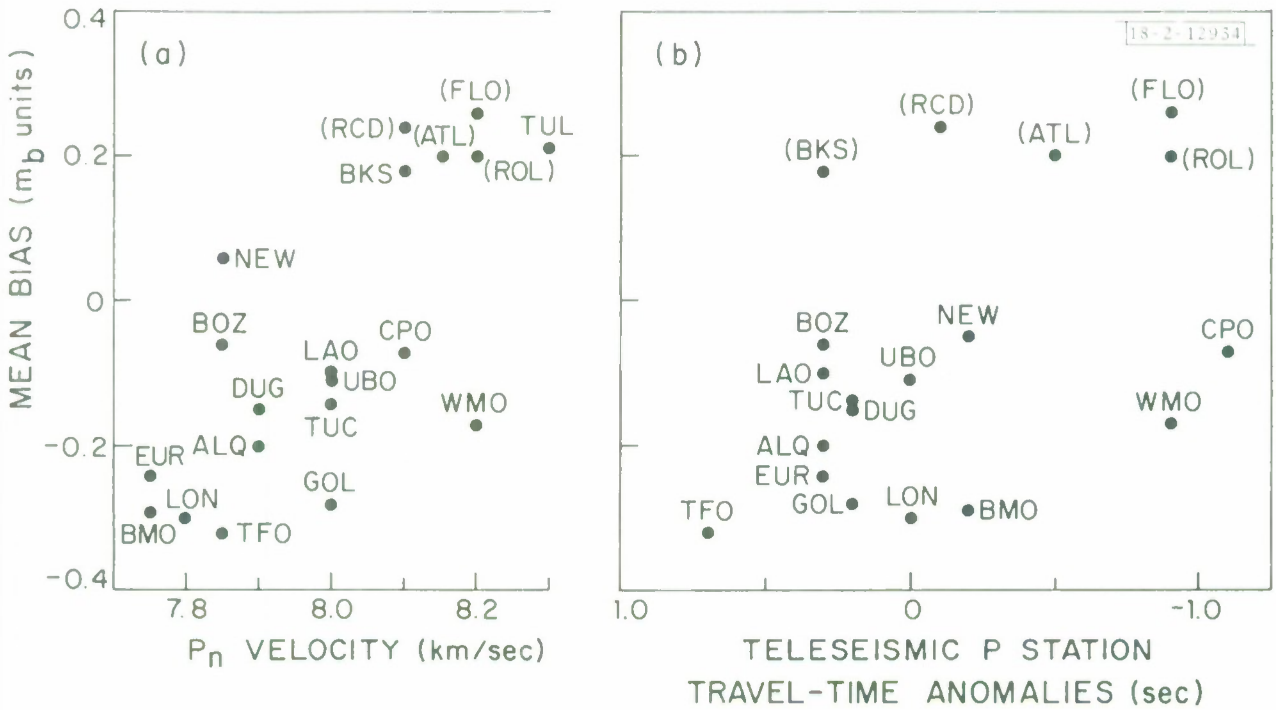

Fig. 14. Mean biases for continental US stations versus

(a) sub-station P_n velocity (from Reference 17)

(b) station P travel-time anomalies (from Reference 18).

IX. APPLICATION OF BIASES AS STATION m_b CORRECTIONS

As well as their intrinsic geophysical interest, a clear application of the biases we have obtained is their use as station corrections to reduce scatter in the determination of m_b for a particular event. We may correct each individual station m_b by

$$m_b = m_b - \text{bias}$$

This method is analogous to the joint epicentre determination technique of Douglas[19] which uses travel time residuals from a large, well-recorded (master) event as station travel-time corrections for smaller events nearby. The epicentres are then relocated relative to the master event. The average (event) m_b values we obtain will also be corrected so that they are more relatively accurate; their absolute values are undetermined.

Ideally we should also apply a bias correction for attenuation in the vicinity of the source, since, as shown in sections V and VII, the station biases as measured here reflect mainly attenuation in the vicinity of the station. Most earthquakes occur in subduction zones and here, as the evidence of, amongst others, Molnar and Oliver[2] has shown, attenuation is high on the concave side of the Pacific island arcs. Reciprocity implies that station bias in seismic regions can be applied as source bias for these regions. The few station biases we have obtained for sites in tectonic regions (Alaska, Japan, South America, New Guinea, and the Caribbean) are however mostly positive (Figure 13) and none are less than -0.2 m_b units. These stations are unfortunately, as mentioned previously, mostly situated relative to teleseismic activity (i.e., $\Delta \geq 21^\circ$ as defined here) such that the known zones of high attenuation in their vicinity are poorly sampled. Thus we cannot estimate source biases with any degree of accuracy (unless we accept a relation to P_n velocities). This means further that even the m_b values as corrected for bias do not necessarily reflect 'true' m_b corrected to the source, which can only be estimated given a knowledge of source region biases (and also the effects of station detection characteristics).

The biases we have obtained from large events (more than 15 reports) have been applied to the entire set of events (defined such that at least 3 of the 72 stations chosen reported m_b values), and the average m_b values recalculated. Figure 15 shows the magnitude frequency distribution of these 38,316 events prior to and after application of the biases as station corrections. There is little change in the distribution of events for $m_b > 5.5$, but at lower magnitudes a substantial redistribution has taken place towards higher magnitudes. This is caused by the disproportionate contribution of western U.S. stations, all with negative biases, to the total number of station magnitude reports, and will be discussed in the next section.

We now wish to test whether the application of these biases has improved the accuracy, or decreased the scatter, of the individual station observations relative to the average m_b for a particular event. Clearly it will do so for the larger events (nearly all of $m_b \geq 5.0$) from which we have derived the biases.

We define the 'scatter' of station m_b observations relative to the average m_b by

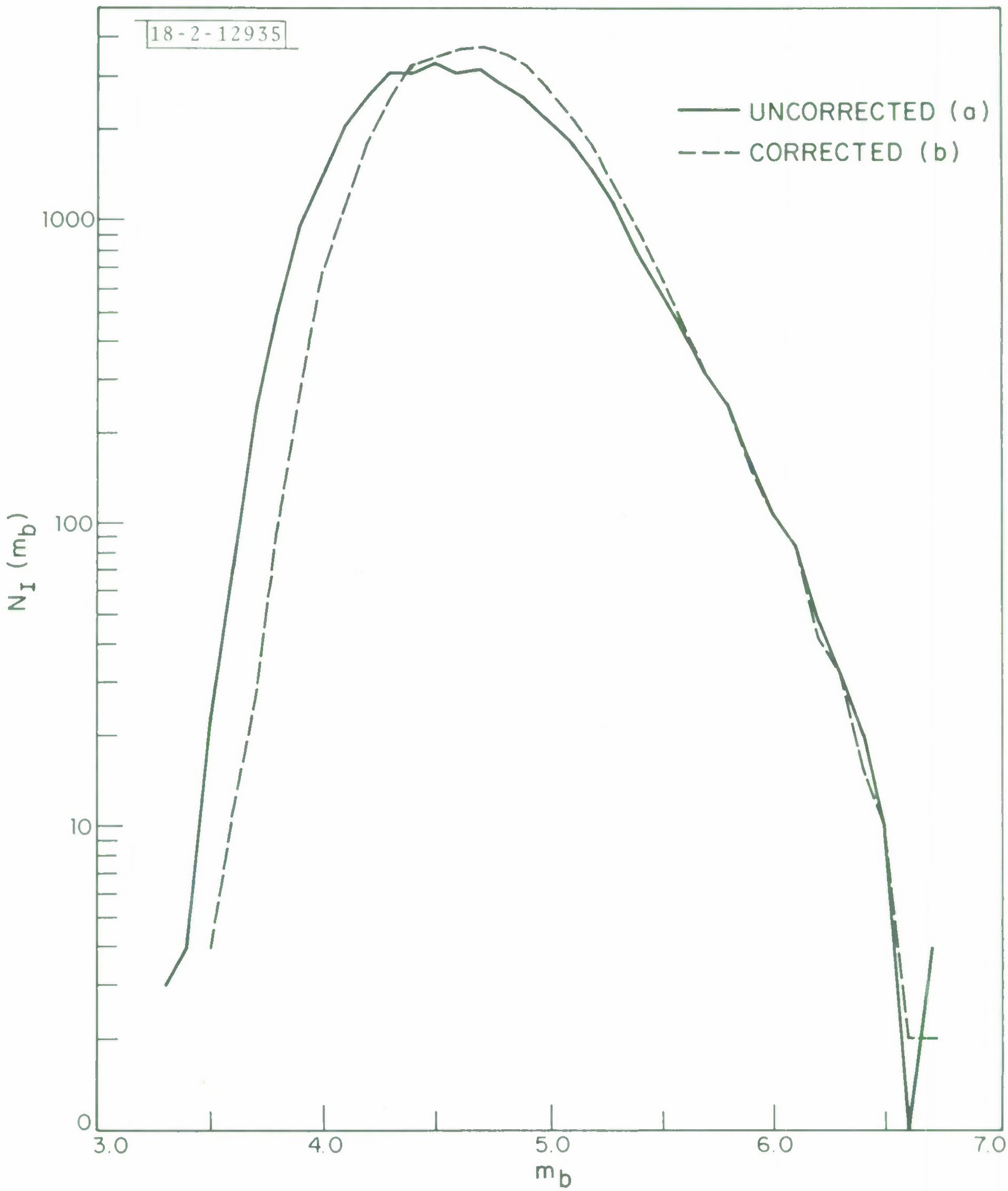

Fig. 15. Incremental magnitude-frequency curves (as defined in Fig. 3) for 38,316 events over 1964-73 with m_b values reported by 3 or more of the 72 stations chosen, prior to (a) and after (b) application of mean biases as station magnitude corrections.

$$\sqrt{\frac{\sum_{i}^{N_e} \sum_{j}^{N_i} (m_{ij} - \overline{m}_i)^2}{N_r - N_e}}$$

for events in a particular magnitude range $m_b \rightarrow m_b + \Delta m_b$, where N_e is the total number of events in the magnitude range, with N_r associated station observations, there being N_i (≥ 3) observations m_{ij} for each event of average magnitude $\overline{m}_i$.

Figure 16 shows the scatter as defined above for $\Delta m_b = 0.1$ m_b unit classes for $3.0 \leq$ average $m_b \leq 6.7$ for both the uncorrected and corrected datasets. We can see that application of the biases has decreased the scatter by at least 15% in the range 4.3 - 6.0 m_b. Below $m_b = 4.0$ the scatter has been increased: this is presumably because the effects of detection characteristics are particularly severe here. Clearly we could have further reduced the scatter by applying different station biases for each seismic region (and year!). Unfortunately we could find little rational explanation for the yearly variation in station bias, and no consistency in regional biases across small receiver regions; these problems should be solved before more sophisticated bias corrections are applied.

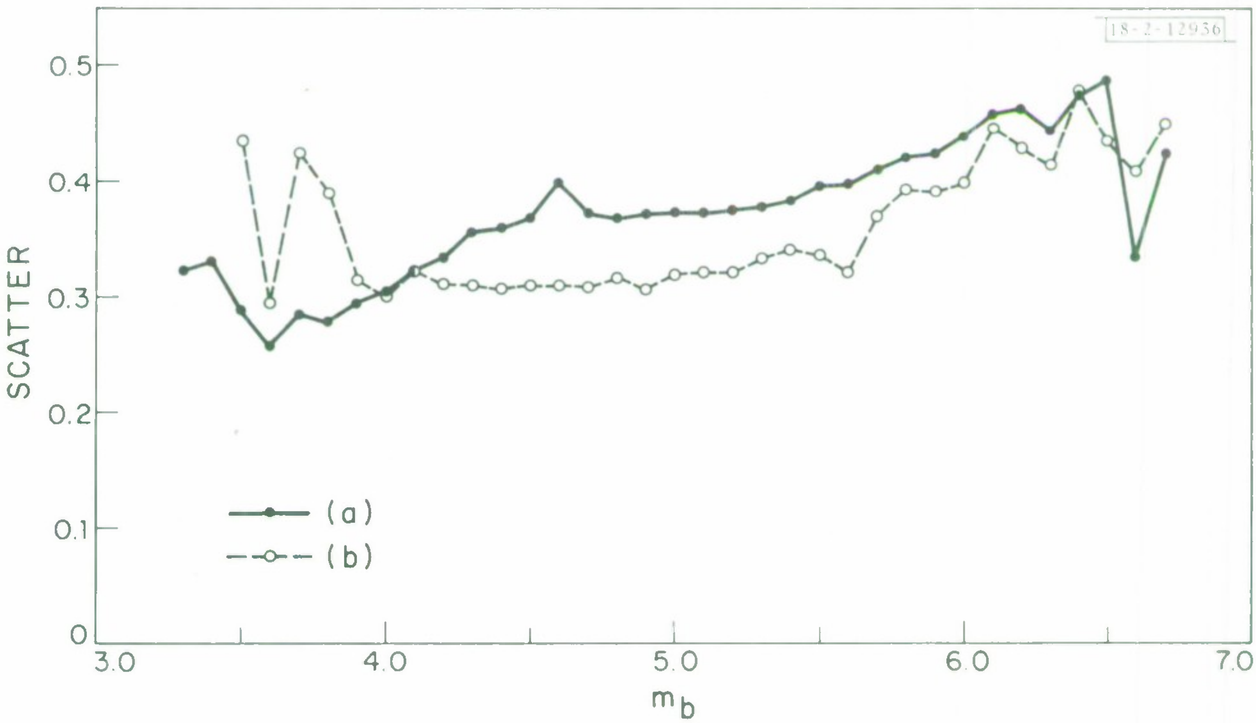

Fig. 16. Scatter, as defined in the text, as a function of m_b (each point denotes scatter for all events of $m_b \rightarrow m_b + 0.1$) before (a), and after (b) application of station m_b corrections. Only events reported by 3 or more of 72 stations are used.

X. STATION DISTRIBUTION AND APPARENT CHANGES IN SEISMICITY

Table I shows that for the first 6 years of the time period 1964-73 considered here a very large proportion of all station reports were from stations in the U.S. This proportion declined considerably over 1970-73. In particular, 5 Vela stations (BMO, CPO, TFO, UBO, and WMO), which were operated as short period arrays, and two other stations in the Western U.S. (DUG, EUR) contributed a vast number of station reports in earlier years. WMO and CPO, although in the eastern U.S. province of Figure 6, have negative biases unlike other stations in the same region: this may be partly due to the response characteristics of the instruments, which are capable of recording much shorter period signals than normal (e.g., WWSSN) stations[20]. Division of reported amplitude A by dominant period T does not entirely compensate for the much higher attenuation at shorter periods. Table 1 of Evernden and Clark[5] also appears to show that magnitude biases for WMO and CPO are anomalously low compared to other stations in the Eastern U.S. province. The effect of these stations, and others in the Western U.S. which have large negative biases, is a noticeable reduction in average m_b values, particularly at lower magnitudes. This has been noted in the previous section in the discussion of Figure 15.

Figure 17 shows the total number of station m_b reports per year for

- (i) all stations, events of $N_{st} \geq 3$, N_{st}=station reports/event
- (ii) 72 stations, events of $N_{st} \geq 3$
- (iii) 14 stations in continental U.S. (7 stations below plus ALQ, BOZ, GOL, LAO, LON, NEW, TUC)

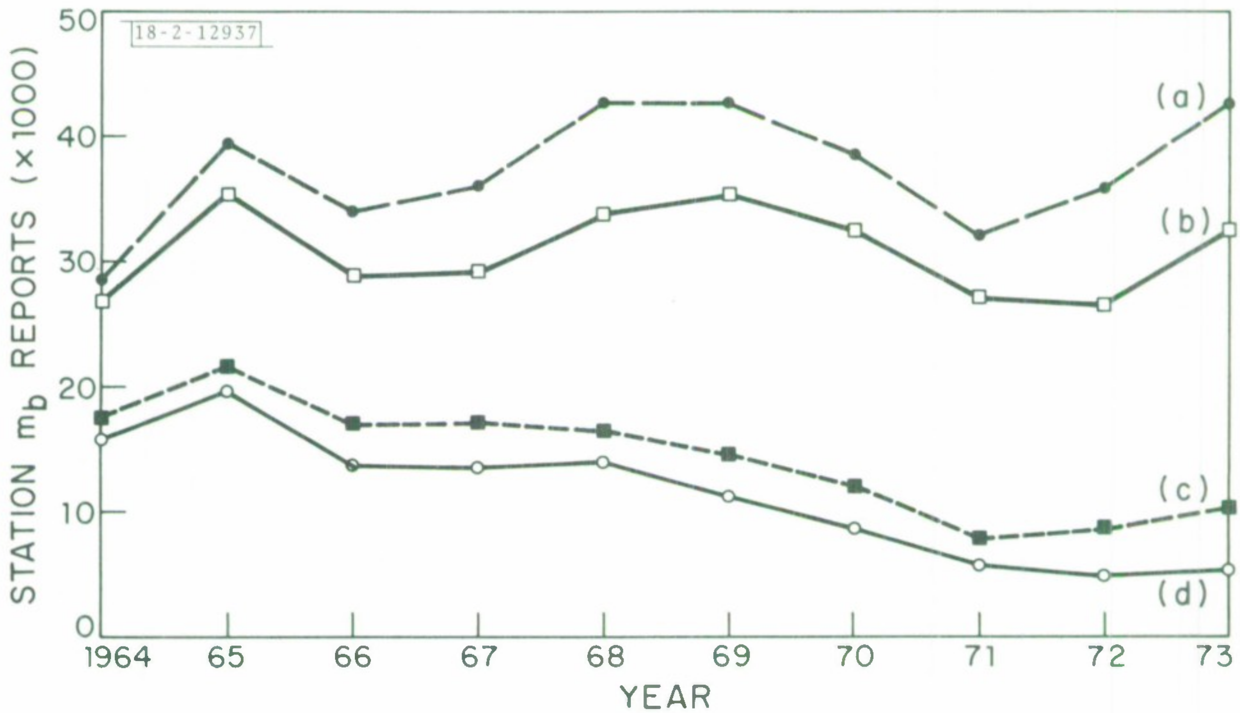

Fig. 17. Total station m_b reports/year from

(a) all stations
(b) 72 stations chosen
(c) 14 US stations
(d) 5 Vela stations plus DUG, EUR.

(iv) the 7 stations BMO, CPO, TFO, UBO, WMO, DUG, and EUR.

During 1964-69 stations in category (iii) above contributed from 45 to 65% of all station m_b observations, and those in category (iv) from 32 to 58%. These proportions decline to ∿30% and ∿20% respectively in 1970-73. Some of the Vela stations ceased to operate as arrays (UBO, CPO) or stopped reporting altogether (TFO, WMO) in 1969-70.

The reporting performance of the Vela stations is truly remarkable, as shown in Figure 18, - BMO never reported less than 50% of all events of $N_{st} \geq 3$ for our 72 station data set in any one given year and in 1964-65 UBO reported over 80% of all events. The number of events reported by at least 3 stations (all stations, not just the 72 chosen here) has varied (see last row of Table I) from 3170 to 5132; the lowest number is for 1970, when some Vela stations stopped or reduced their reporting; the highest is for 1965, in which the Rat Island sequence contributed over 1000 events.

Figures 19 and 20 illustrate the variation in magnitude distribution due to the changing contribution with time of the 7 stations of category (iv) above with low biases. Figure 19a shows the average number of events/year, uncorrected for bias, for 1964-69 and 1970-73. As well as a considerable reduction in the number of smaller events for the later period (and in the annual number of events from 4096 to 3433), there is also a redistribution of events towards higher magnitudes. Application of the biases (Figure 19b) reduces the apparent difference in seismicity for these two time periods considerably, though there is still a marked reduction in the number of smaller

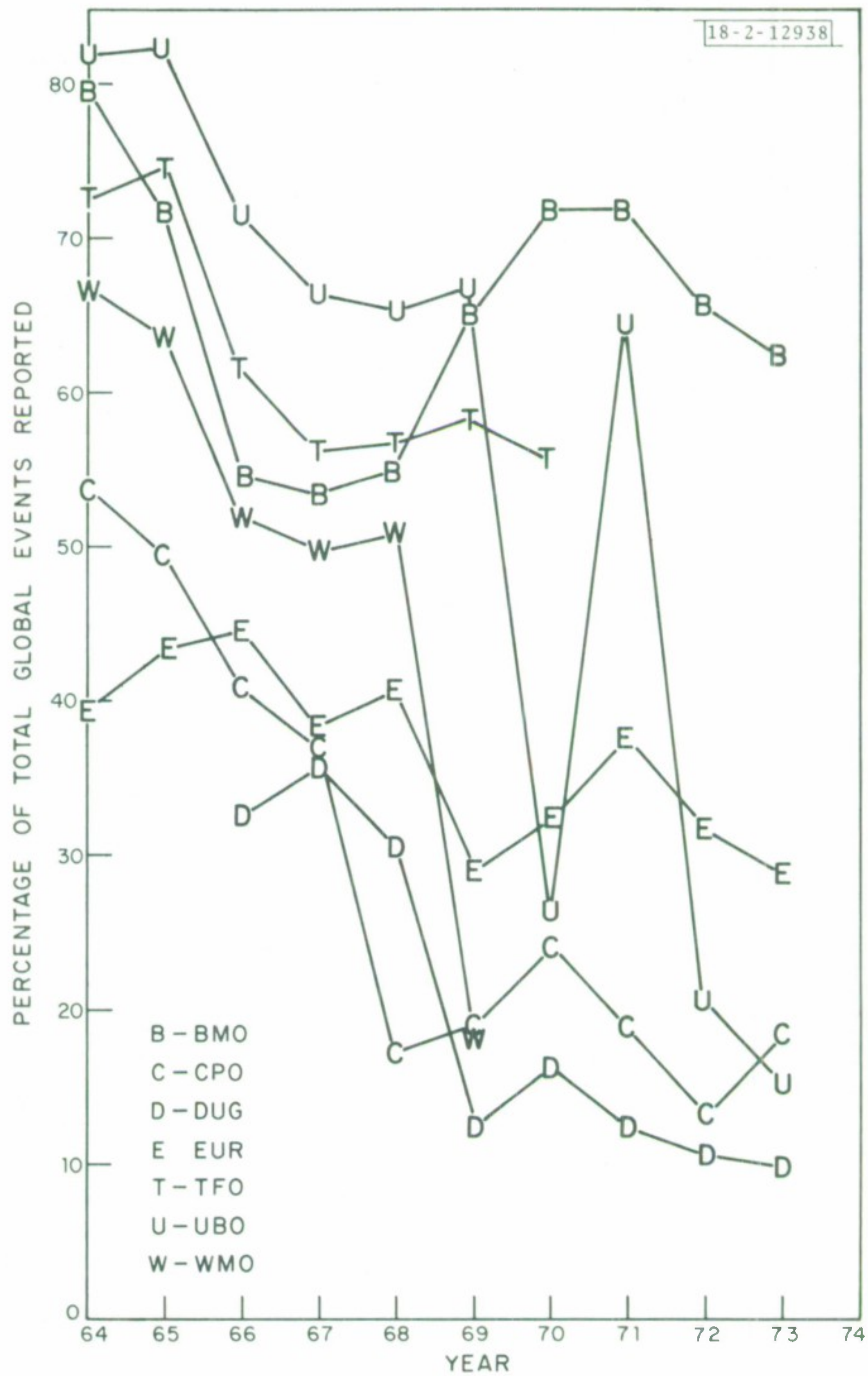

Fig. 18. Percentage of total global events (3 or more of 72 stations reporting m_b) for which m_b values have been given by 5 Vela stations, DUG, and EUR, per year.

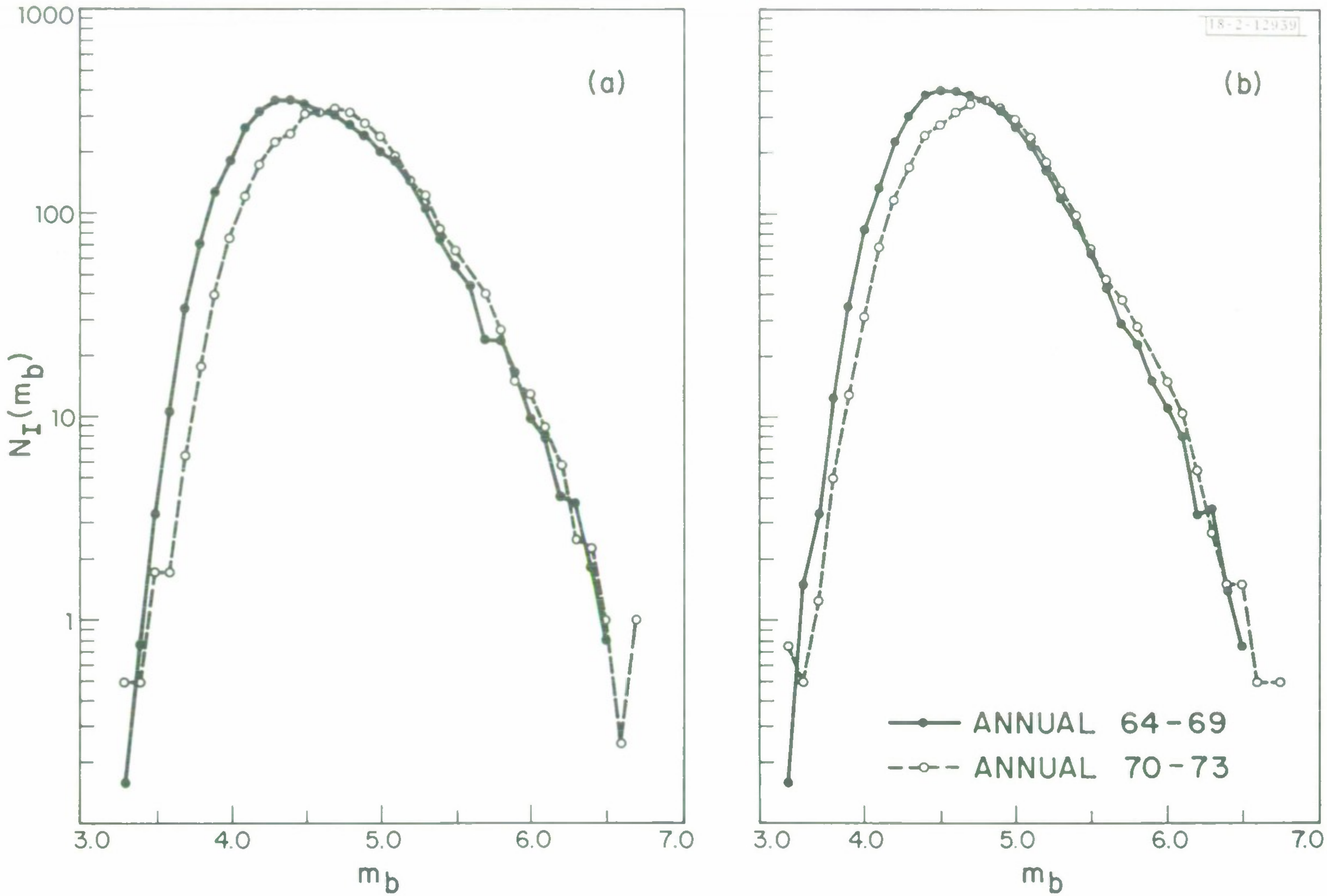

Fig. 19. Incremental magnitude frequency curves, reduced to annual rates for 1964-69, 1970-73, prior to (a) and after (b) application of station m_b corrections.

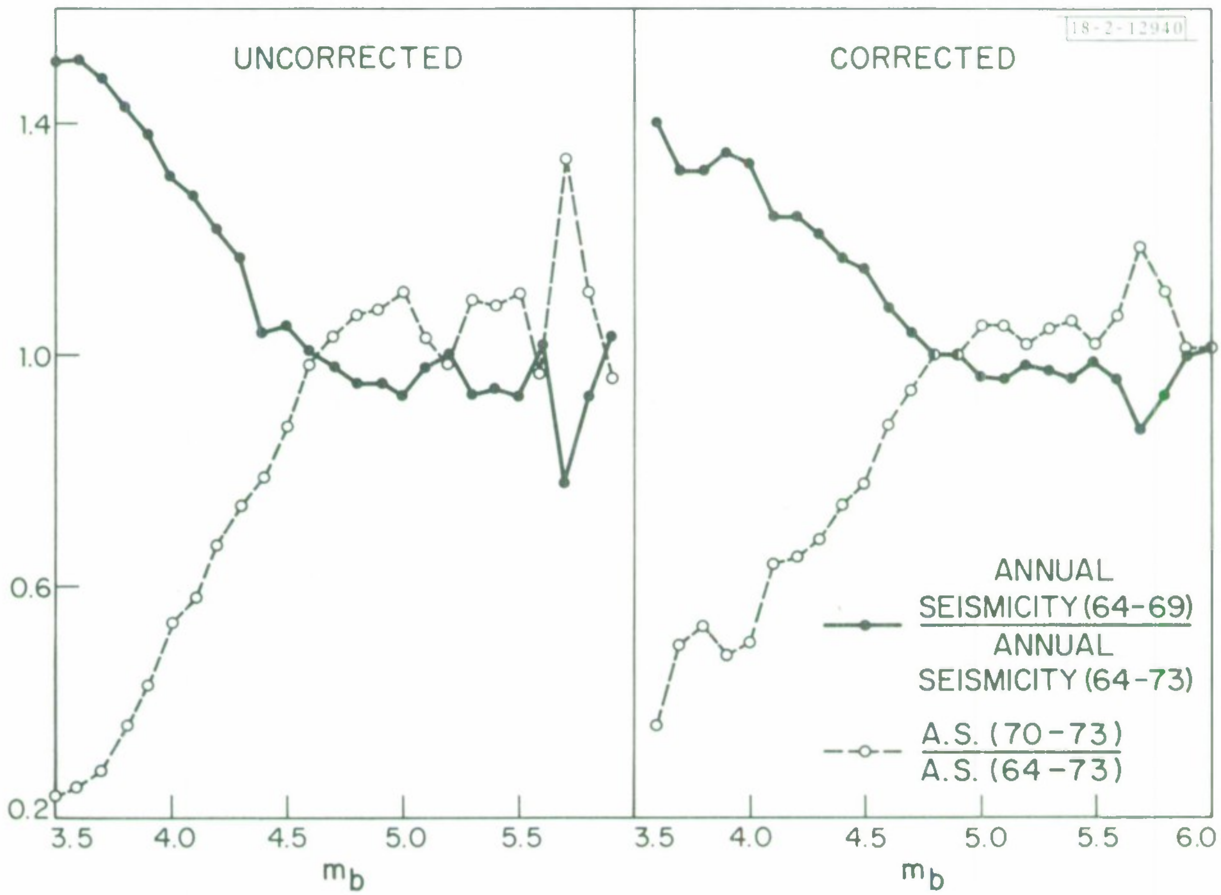

Fig. 20. Ratios of annual seismicity, 1964-69 and 1970-73, to annual seismicity, 1964-73, as a function of m_b (0.1 magnitude classes) before and after station corrections have been applied.

events for 1970-73 compared to 1964-69. Figure 20 expresses the difference in another manner, and shows the ratios of the annual number of events in a given 0.1 m_b range for 64-69 and 70-73 to that for the entire time period 1964-73. The difference from mean seismicity (1964-73) for $m_b = 4.8$ is reduced by a factor of 2 on application of the biases as station m_b corrections. There is still an apparent increase in seismicity for the later time period: this is possibly because the negative biases for Western U.S. stations are underestimated since the average event m_b for 1964-69 is reduced by the disproportionate contribution of these stations. It is clear that network detection capability has been seriously degraded by the closure or reduction in reporting ability of these Vela stations. It is somewhat paradoxical that although there are more stations reporting in later years they do not do as well at lower magnitudes as the fewer stations of 1964-69.

Figure 21 gives the number of events of $m_b \geq 3.0$, 4.0, 4.5, 5.0, 5.5, and 6.0 reported in each year. It can be seen that with the exception of a obvious low in 1966-67[21] the number of events of $m_b \geq 5.0$ has remained effectively constant as measured by our 72-station network, and $m_b = 5$ is clearly close to the detection ability of the network for all years. Note that the aftershocks of the Alaskan earthquake of 1964, and the Rat Island sequence of 1965, have not been removed from the seismicity. Application of the biases has not substantially changed the annual numbers of events of $m_b \geq 5.0$.

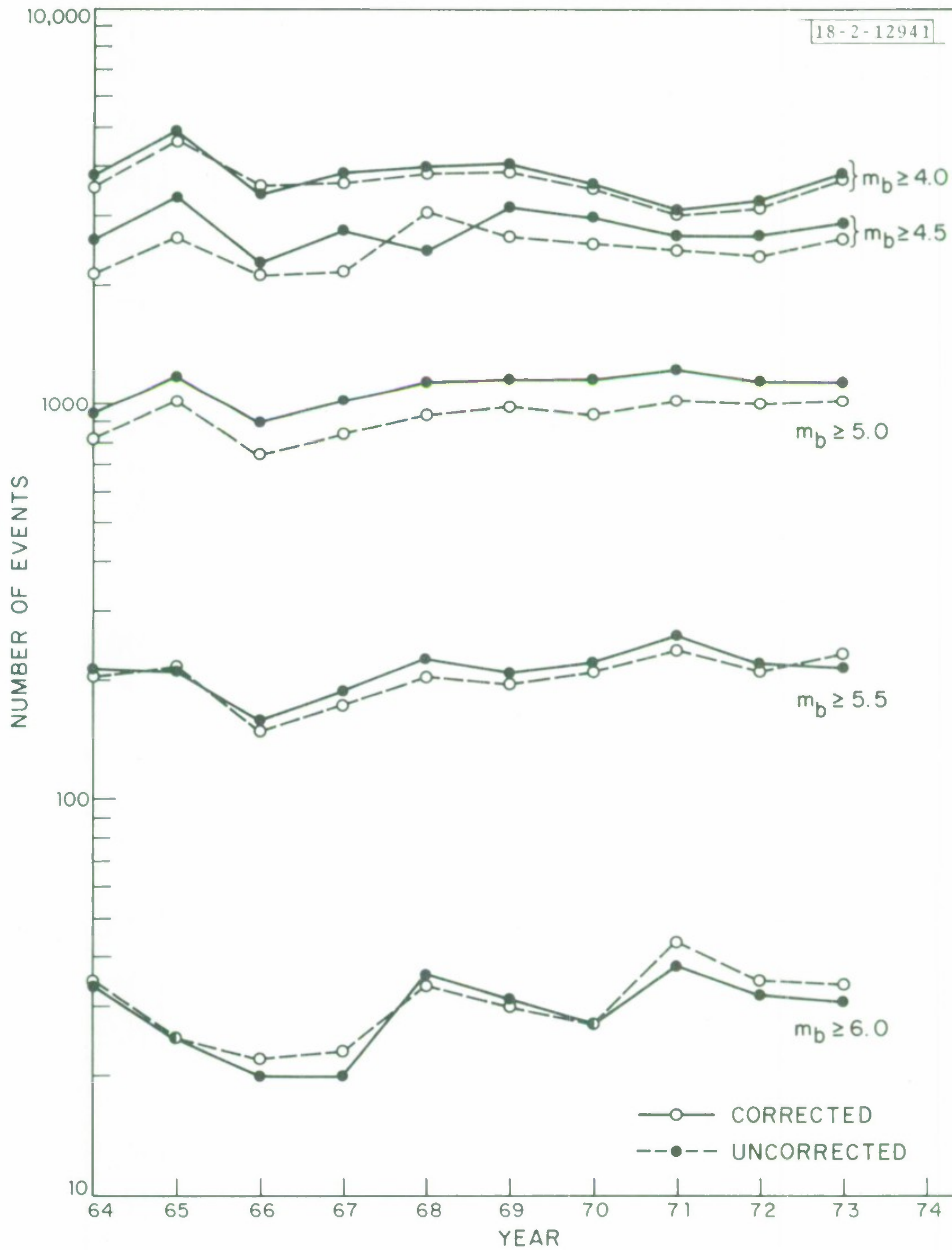

Fig. 21. Annual number of events, reported by 3 or more stations of 72-station network, $m_b \geq 4.0$, 4.5, 5.0, 5.5 and 6.0, before and after station corrections have been used.

XI. APPLICATIONS TO SEISMIC DISCRIMINATION

Use of the station biases given here will probably reduce the scatter in the $M_s:m_b$ diagram, though the biases are not large enough to greatly improve the separation of the earthquake and explosion populations. If one also takes into account biases introduced in the source region (which we have unfortunately been unable to determine because of the lack of stations in seismic regions) the improvement could be dramatic.

The application of both source and receiver biases can, as demonstrated by Marshall[16], dramatically improve the linearity of the magnitude-yield relation. The combined effects of source and receiver biases is such that, for example, an explosion of given yield detonated in the Lake Baikal region (rift structure and therefore presumably large negative bias) and recorded in the Western U.S., will give an m_b up to 0.8 units lower than that for one of the same yield in Eastern Kazakhstan (stable aseismic platform) reported in Canada and the Eastern U.S. Station and source may well, in certain instances, be geographically located such that such large variations in m_b for a given yield may become a reality.

The results of this study of bias also demonstrate the dangers of assigning event magnitudes on the basis of one station report only (as done, for example, by the NEIS Earthquake Data Reports). For a station whose biases with respect to the mean of a large network of stations are distributed normally with mean -0.3 and standard deviation 0.35 m_b units (typical Western U.S. values) there exists a probability of 0.50 that the station magnitude will be lower by 0.3 m_b units, and a probability 0.20 that it will be lower by 0.6, than the average of a large network observing the same event. This is one of the justifications for studying here only events for which m_b has been reported by 3 or more stations (except that if all these 3 are in the Western U.S. we are no wiser!). A more comprehensive statistical analysis of m_b, taking into account random variations, biases, and the effects of detection thresholds, such as that proposed by Ringdal[19] and Christoffersson et al.[11] is clearly desirable.

XII. CONCLUSIONS

We have shown, using a network of the best 72 stations for 1964-73, that there exist substantial station biases (up to at least 0.4 m_b units) as measured relative to average m_b. These biases are well correlated with tectonic structure and previous measurements of lateral variations in attenuation. There is also some evidence that bias is correlated with P-velocity in the upper mantle (P_n). Application of these biases to the calculation of average m_b for a particular event reduces the scatter in the average m_b and also removes many of the apparent changes in seismicity with time, despite the fact that the biases themselves are clearly a function of source region (and occasionally time!). If the seismic research observatory (SRO) stations now being installed, which have much the same fairly broad-band short period response as the Vela stations, are operated and read as well as the latter, their detection capability should be much better than that of the existing global station network.

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APPENDIX A

GEOGRAPHICAL LOCATIONS OF STATIONS USED IN TABLES II AND IV

Asterisk (*) denotes array operation for some or all of 1964-73; (W) denotes WWSSN station.

ABU	Abuyama, Honshu, Japan
ALE	Alert, Northwest Territories, Canada
ALQ (W)	Albuquerque, New Mexico
ASP	Alice Springs, Northern Territory, Australia
ATL (W)	Atlanta, Georgia
BHA	Broken Hill, Zambia
BKS (W)	Berkeley, California
BMO*	Blue Mountains, Oregon
BNG	Bangui, Central African Republic
BNS	Bensberg, West Germany
BOZ	Bozeman, Montana
BRG	Berggiesshubel, East Germany
BUH	Buhlerhohe, West Germany
BUL (W)	Bulawayo, Rhodesia
CAN	Canberra, Capital Territory, Australia
CAR (W)	Caracas, Venezuela
CIR	Chiredzi, Rhodesia
CLL	Collmberg, East Germany

CLK	Chileka, Malawi
COL (W)	College, Alaska
COP (W)	Copenhagen, Denmark
CPO*	Cumberland Plateau, Tennessee
CPO*	Cumberland Plateau, Tennessee
DAG (W)	Danmarks Havn, Greenland
DUG (W)	Dugway, Utah
EDM	Edmonton, Alberta, Canada
EKA*	Eskdalemuir, Scotland
ESK (W)	Eskdalemuir, Scotland
EUR	Eureka, Nevada
FFC	Flin Flon, Manitoba, Canada
FLO (W)	Florissant, Missouri
FUR	Furstenfeldbruck, West Germany
GBA*	Gauribidanur, India
GDH (W)	Godhavn, Greenland
GIL	Gilmore Creek, Alaska
GOL (W)	Golden, Colorado
GRF*	Grafenberg, West Germany
HFS*	Hagfors, Sweden
HYB	Hyderabad, India
ILG	Inge Lehmann, Greenland
INK	Inuvik, Northwest Territories, Canada
KBL (W)	Kabul, Afghanistan

KEV (W)	Kevo, Finland
KHC	Kasperske Hory, Gzechoslovakia
KJF	Kajaani, FInland
KJN	Kajaani, Finland
KLG	Kalgoorlie, Western Australia
KOD (W)	Kodaikanal, India
KON (W)	Kongsberg, Norway
KRA	Krakow, Poland
KRR	Karoi, Rhodesia
KTG (W)	Kap Tobin, Greenland
LAO*	LASA, Montana
LHN	Lillehammer, Norway
LJU	Ljubljana, Yugoslavia
LON (W)	Longmire, Washington
LOR (W)	Lormes, France
LPB (W)	La Paz, Bolivia
LPS (W)	La Palma, El Salvador
MAW	Mawson, Antarctica
MBC	Mould Bay, Northwest Territories, Canada
MOX	Moxa, East Germany
MTD	Mount Darwin, Rhodesia
MUN (W)	Mundaring, Western Australia
NAO*	NORSAR, Norway
NDI (W)	New Delhi, India

NEW (W)	Newport, Washington
NIE	Niedzica, Poland
NOR (W)	Nord, Greenland
NP-	North Pole, Northwest Territories, Canada
NUR (W)	Nurmijarvi, Finland
OIS	Oishiyama, Honshu, Japan
PAE	Paea, French Polynesia
PMG (W)	Port Moresby, Papua
PMO	Pomariorio, French Polynesia
PMR	Palmer, Alaska
PNS (W)	Penas, Bolivia
PNT	Penticton, British Columbia, Canada
POO (W)	Poona, India
PPN	Papenoo, French Polynesia
PPT	Papeete, French Polynesia
PRE (W)	Pretoria, South Africa
PRU	Pruhonice, Czechoslovakia
RAB (W)	Rabaul, New Britain
RCD (W)	Rapid City, South Dakota
RES	Resolute Bay, Northwest Territories, Canada
RIV (W)	Riverview, New South Wales, Australia
ROL	Rolla, Missouri
RUV	Rauvai, French Polynesia
TFO*	Tonto Forest, Arizona

TPT	Tiputa, French Polynesia
TRN (W)	Trinidad, Trinidad and Tobago
TSK	Tsukuba, Honshu, Japan
TUC (W)	Tucson, Arizona
TUL (W)	Tulsa, Oklahoma
TVO	Taravao, French Polynesia
UBO*	Uinta Basin, Utah
VAH	Vaihoa, French Polynesia
WIN (W)	Windhoek, Namibia
WMO*	Wichita Mts. Oklahoma

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An analysis of some 400,000 station m_b values as reported in the ISC bulletin reveals substantial global variations in station magnitude bias, defined as the mean difference between station m_b and the average m_b of a large network of stations. Although there are clear indications that the biases are functions of both source region and time, they appear to be well correlated with tectonic structure and lateral variations in attenuation characteristics in the upper mantle under the station. Application of these biases as station magnitude corrections reduces the scatter in m_b observations for a single event. Changes in station distribution with time are shown to introduce perceptible temporal changes in the shape of magnitude-frequency curve; these can be greatly reduced by application of the station corrections. These corrections, through their effect on the M_s:m_b diagram and the magnitude-yield relation, are applicable to the problems of seismic discrimination.

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