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Seismicity Variations in the Makran Region of Pakistan and Iran: Relation to Great Earthquakes†

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Abstract – Teleseismic activity in the Makran region of southeastern Iran and southwestern Pakistan prior to the great earthquake ($M_s = 8$) of 1945 can be characterized in terms of two stages. First, during the period 30 (or more) to 10 years prior to the main event, the frequency of occurrence of moderate to large earthquakes was relatively high in the region between the impending rupture zone and the volcanic arc to the northwest. These events probably occurred near the down-dip limit of seismic activity within the subducted slab. Second, activity was concentrated along the coast during the ten years immediately preceding the great earthquake and most of this activity was confined to the vicinity of the epicenter of the 1945 earthquake. These patterns are similar in some respects to those observed prior to some large earthquakes in other parts of the world.

Three observations concerning the pre-1945 seismicity suggest it was associated with the preparation for rupture of the zone that eventually broke during the great earthquake in 1945: (1) The activity before 1945 is located either within the 1945 rupture zone or between this zone and the volcanic arc to the northwest; (2) No activity of similar magnitude and occurrence rate is observed elsewhere along the Makran plate boundary; and (3) The region that was active prior to 1945 has been relatively quiet since the decline in aftershock activity associated with the 1945 shock. The current quiescence may be related to the release of stress during the 1945 earthquake.

Recent seismicity in the region west of that affected prior to 1945 suggests that this western region may be the site of the next large earthquake. Events along the coast are grouped at both ends of a seismically quiet zone, producing a distribution similar to the 'donut' pattern identified by Mogi. In addition, one moderate-magnitude earthquake occurred within the subducted slab to the northwest of the donut pattern along the coast. This moderate-magnitude earthquake, the first to occur in the region immediately west of the 1945 rupture zone since the advent of instrumental recording, may be analogous to the activity of stage one associated with the 1945 earthquake. While by no means providing conclusive evidence of an impending earthquake, the characteristic patterns identified in the recent seismicity indicate that this region should be closely monitored in the future.

Key words: Earthquake prediction; Seismic gaps; Tectonics Iran; Tectonics Pakistan

Introduction

The Makran region of southwestern Pakistan was the site of a great earthquake on 27 November 1945. This earthquake, which had a surface-wave magnitude of 8

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(GELLER and KANAMORI, 1977), caused widespread damage along the Pakistani coast and probably reached an intensity of X–XI (modified Mercalli scale) at the towns of Pasni and Ormara (INTERNATIONAL SEISMOLOGICAL SUMMARY – 1945, 1954; PAGE *et al.*, 1978). The distribution of intensities and the long-term aftershock activity suggest the length of the rupture zone was between 100 and 200 km.

A number of patterns in the spatial and temporal distribution of seismicity are cited as phenomena associated with the occurrence of large earthquakes around the world. These patterns include an increase in activity at depth prior to large shallow shocks (MOGI, 1973), characteristic variations in the rates of occurrence and locations of earthquakes (e.g. MOGI, 1969; KELLEHER and SAVINO, 1975; OHTAKE *et al.*, 1977), relationships between interplate and intraplate earthquakes (SHIMAZAKI, 1976, 1978), and earthquakes that cluster in time and space (e.g. EVISON, 1977; HABERMANN and WYSS, 1977, 1979; CAPUTO *et al.*, 1978). Not all of the patterns discussed in the literature are observed before every earthquake, but most are identified before at least several large events.

In this paper variations in the distribution of teleseismic activity for the Makran region of southeastern Iran and southwestern Pakistan are examined in light of such seismicity patterns. Activity occurring before the Makran coast earthquake in 1945 appears to be consistent with some aspects of previously identified patterns. Limited data from recent years lead to the speculation that a similar large event may occur immediately west of the 1945 rupture zone in the future. It is not possible, however, to estimate with existing data the time of occurrence of such a potential shock.

Tectonic Setting

The Makran region is interpreted by a number of workers as a zone of active subduction (e.g. STONELEY, 1974). Although a bathymetric trench is not observed offshore, most other features of a typical subduction zone can be identified. Sediment deformation, revealed by seismic reflection profiles off the Makran coast, is similar to that at other compressive plate boundaries (WHITE and KLITGORD, 1976). FARHOUDI and KARIG (1977) find that the structures, sedimentary deposits and topography of the Makran area can be readily interpreted in terms of a standard model for an accretionary prism. In addition, centers of Quaternary volcanism, which are characterized by rocks of andesitic composition (GANSSER, 1971; GIROD and CONRAD, 1975), form a northeasterly trending lineament that is located north of the accretionary prism (Fig. 1).

The seismicity of the Makran region is consistent with its interpretation as an active subduction zone (FARHOUDI and KARIG, 1977; JACOB and QUITTMEYER, 1979). The teleseismic activity defines a shallow dipping seismic zone that extends to depths of about 80 km just south of the volcanic arc (Fig. 2). In addition, fault plane solutions for two of the earthquakes located near the down dip limit of the proposed Benioff zone (events A and B in Fig. 2), exhibit down-tip tension as would be expected in such

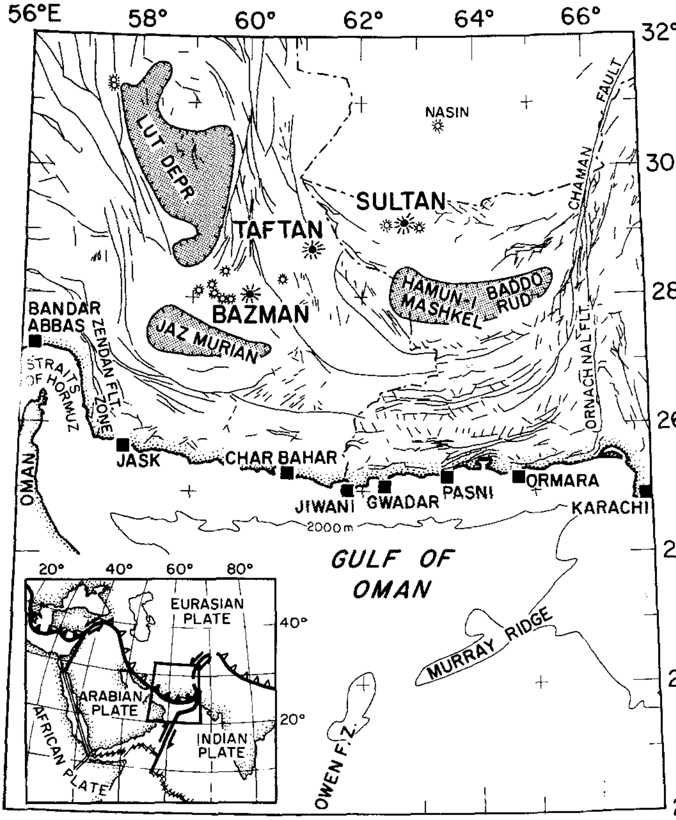

Figure 1

Regional setting of the Makran coast in Pakistan and Iran. The Makran coast is interpreted as a region of active subduction. The accretionary prism rises to the north from the Gulf of Oman. It is bordered to the north first by the fore-arc basins (Jaz Murian and Hamun-i-Mashkel) and then by the volcanic arc. The main centers of Quaternary volcanism are the Bazman, Taftan and Sultan volcanoes. Raised marine terraces are observed along the coast from Jask to Ormara. The Makran coastal zone is bordered to the west by the Zendan fault zone and the Oman spur, and to the east by the Ornach-Nal and Chaman faults. A simplified plate tectonic setting is shown in the inset. The mapped faults in Iran are from BERBERIĀN (1976) and in Pakistan from BAKR and JACKSON (1964). Volcano Nasin is of carbonitite composition and not related to the volcanic arc farther south.

a subduction zone (ISACKS and MOLNAR, 1969). The relatively small number of earthquakes that occur in this region do now allow the direction of dip to be precisely defined; it is approximately northward.

Data

The earthquakes used in this study are listed in Table 1. Events occurring prior to 1965 were systematically relocated using a computer program similar to the one

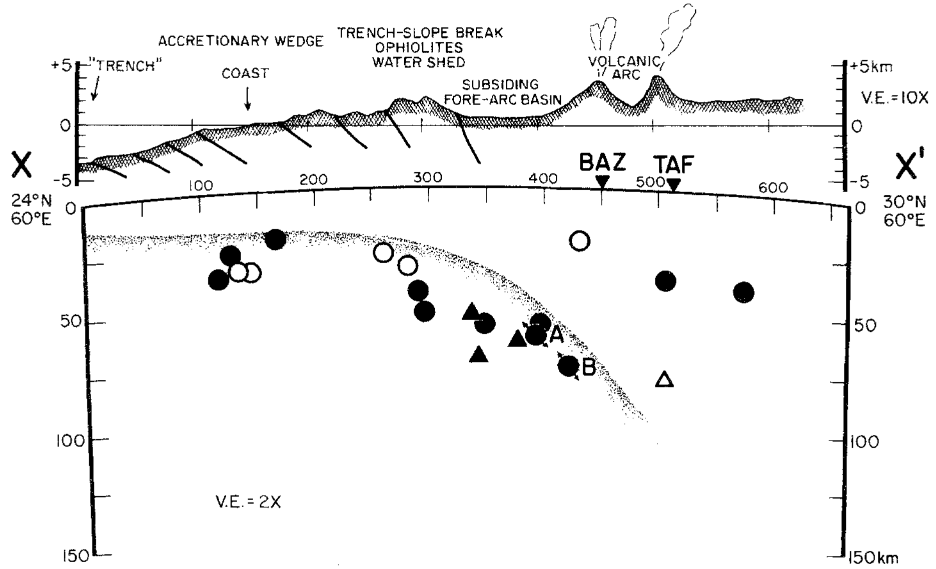

Figure 2

Cross section through the western Makran region showing the earthquake hypocenters and inferred dipping Benioff zone (bottom), and topography and some surface tectonic features (top) along the same profile. The section is along longitude 60°E, between latitudes 24 and 30°N. *Bottom:* Circles represent events up to 200 km to the east of the section line, triangles up to 200 km to the west. Filled symbols represent events for which the depth is constrained by at least one reported depth phase; open symbols represent events for which the depth is determined by minimizing the residuals of first P arrivals only. Average depths determined independently by these two methods usually differ by no more than 10 km in cases when both are available in this region. The arrows at the two hypocenters labelled A and B show the plunges of the T axes for these two events, taking into account the 2X vertical exaggeration. The shaded band is the inferred upper boundary of the descending oceanic lithosphere belonging to the Arabian plate. *Top:* Major tectonic features and subdivisions of the trench-volcano gap in the western Makran. Note the different vertical exaggerations in top and bottom of the figure. From JACOB and QUITTMEYER (1979).

described by BOLT (1960). This procedure reduces relative location errors that result from the use of different travel-time tables and different location methods. It will not, however, produce locations that are more accurate than the reported arrival times or the values of travel-time (Jeffreys-Bullen table) that are used as input.

Magnitudes are compiled from GUTENBERG and RICHTER (1954), ROTHÉ (1969), GELLER and KANAMORI (1977) and the bulletins of the INTERNATIONAL SEISMOLOGICAL CENTRE (1964–1975) and various U.S. governmental agencies (e.g. U.S. COAST AND GEODETIC SURVEY, EARTHQUAKE DATA REPORTS (EDR), PRELIMINARY DETERMINATIONS OF EPICENTERS (PDE)). When possible, magnitudes for events not included in these sources are computed from values of ground displacement amplitude that are reported in the station bulletins of Uppsala, Sweden, and DeBilt, Netherlands. The procedure employed is similar to that used by QUITTMEYER and JACOB (1979). QUITTMEYER and JACOB (1979) found, however, that the use of the Uppsala and DeBilt

Table 1

Earthquakes located in the Makran region of Pakistan and Iran

DATE			ORIGIN TIME	LATITUDE[1]	LONGITUDE[1]	FE REG[2]	DEPTH[3]	MAGNITUDE[4]	NO STA[5]	S.E. RESD	Q[6]	SRC[7]
DY	MN	YR										
24	10	19	203215.0	27.50*00	63.60*00	354	C033*00	6.1SDBN	000	11.06	D	ISS
19	05	26	211353.2	26.25*13	58.80*09	353	C033*00	5.6SGTR	008	01.27	C	ISS
07	07	27	200622.6	26.98*11	62.15*07	354	C080*00	6.5SGTR	044	01.84	A	ISS
03	09	29	120736.2	26.61*13	61.94*08	354	C080*00	6.5SGTR	043	02.48	B	ISS
04	02	32	211816.4	26.42*10	62.63*13	354	059*32	5.6SGTR	017	01.68	B	ISS
18	04	32	112326.5	25.21*12	63.88*08	354	C033*00	6.0SGTR	025	01.97	B	ISS
21	02	33	190259.1	27.57*16	57.38*09	353	C033*00	5.9SDBN	013	02.13	C	ISS
07	07	33	073057.7	24.23*15	64.92*08	356	C033*00	5.6SGTR	008	01.32	C	ISS
19	04	34	232603.8	24.06*11	65.38*17	356	C033*00	5.6SGTR	007	01.63	C	ISS
13	06	34	221023.6	27.71*09	62.70*04	353	C080*00	7.0SGTR	106	02.14	B	ISS
10	06	36	032909.2	26.30*12	64.01*10	354	C033*00	6.2SDBN	017	02.24	C	ISS
10	06	36	171108.3	25.98*29	64.61*16	354	C033*00	5.9SDBN	011	03.16	D	ISS
11	06	36	094341.7	26.43*27	64.79*16	354	C033*00	5.8SDBN	008	03.17	D	ISS
04	02	38	001903.7	25.60*09	64.49*09	710	C033*00	0.0	010	01.50	C	ISS
07	01	40	090156.9	25.23*12	63.83*10	354	C033*00	0.0	011	02.09	C	ISS
29	10	41	074315.6	25.21*12	63.69*11	354	C033*00	0.0	011	02.33	C	ISS
06	02	43	023600.7	24.89*11	63.25*08	356	C033*00	6.3SGTR	027	02.04	B	ISS
27	11	45	215655.2	25.15*09	63.48*06	354	C033*00	8.0SGGK	060	02.31	B	ISS
11	12	45	102153.1	24.67*44	63.78*37	356	C033*00	0.0	008	06.88	D	ISS
18	12	45	032340.3	25.81*22	63.75*24	354	C033*00	0.0	009	04.25	D	ISS
17	03	46	210600.1	24.99*10	63.59*09	356	C033*00	0.0	014	02.07	C	ISS
27	03	46	233034.5	25.36*09	64.72*07	356	C033*00	0.0	037	02.03	B	ISS
21	06	46	151003.9	24.31*22	64.86*24	356	C033*00	0.0	010	03.91	D	ISS
15	08	46	192519.4	26.71*16	65.57*12	710	C033*00	0.0	022	03.37	C	ISS
05	08	47	142413.7	25.04*08	63.49*05	354	C033*00	7.3SGTR	072	02.10	A	ISS
03	10	47	061346.4	26.08*08	57.32*05	353	C033*00	6.2SGTR	056	01.91	B	ISS
09	12	47	163223.5	24.84*13	63.55*13	356	C033*00	0.0	015	01.91	C	ISS
30	01	48	084355.0	25.16*08	63.78*08	354	039*21	6.8SUPP	050	02.10	B	ISS
01	02	48	233826.9	27.13*32	57.59*09	353	C033*00	0.0	013	02.00	C	ISS
02	01	49	125027.2	25.06*08	64.19*06	354	C033*00	0.0	035	01.95	C	ISS
09	04	49	235548.2	27.18*12	62.26*06	354	C033*00	0.0	010	01.09	C	ISS
21	07	49	212600.7	26.29*32	59.06*23	353	C033*00	0.0	011	03.19	D	ISS
22	11	49	152115.4	28.08*08	57.07*06	353	C033*00	0.0	036	01.92	B	ISS
09	07	50	002839.3	25.62*09	63.31*07	354	124*17	5.8SUPP	068	02.23	B	ISS
14	11	50	220448.8	24.91*06	63.67*07	356	064*18	5.6SUPP	042	01.85	A	ISS
16	08	51	235209.9	27.49*05	57.25*03	353	C029*00	5.7 NOA	092	01.69	A	ISS
30	12	51	182108.5	28.20*06	57.05*04	353	C033*00	5.1SUPP	065	01.94	B	ISS
20	09	52	184121.0	26.95*09	62.00*06	353	C067*00	0.0	012	01.37	B	ISS
28	12	52	184024.5	24.97*04	63.28*04	356	C033*00	4.9SUPP	068	01.70	A	ISS
23	07	53	010547.3	26.71*06	65.20*05	710	036*12	6.3BUPP	040	01.41	A	ISS
29	06	56	021831.7	28.46*07	57.22*05	353	C033*00	5.9BUPP	042	01.56	B	ISS
31	08	58	091821.9	27.66*12	61.99*09	354	082*20	0.0	025	01.77	C	BCI
01	09	58	083708.9	27.76*05	62.72*13	354	157*20	0.0	014	00.56	C	BCI
22	08	59	234812.7	27.61*09	62.26*07	354	061*13	0.0	025	01.16	B	BCI
28	09	61	223625.2	27.29*05	57.03*02	353	037*07	5.6 ROT	075	01.14	A	ISS
01	09	62	150101.9	25.60*05	65.30*04	710	C033*00	5.9 ROT	095	01.88	A	ISS
29	09	62	065359.9	28.29*08	57.48*04	353	083*08	5.5 MOS	033	01.06	B	BCI
24	01	63	154217.8	28.29*17	57.01*05	353	078*11	0.0	029	01.65	C	BCI
29	05	63	083506.6	27.17*06	59.46*03	353	C071*00	5.7 ROT	081	01.36	A	ISS
12	08	63	182939.7	25.32*06	62.74*04	354	C033*00	5.4 ROT	069	01.86	B	ISS
27	09	63	170922.6	27.27*10	65.92*06	710	C033*00	4.7BCGS	026	01.78	C	BCI
16	10	63	190228.0	28.21*08	57.85*04	353	096*10	4.8BCGS	041	01.43	B	BCI
11	03	64	233419.7	28.57*17	57.85*16	353	C033*00	4.7BISC	024	01.88	C	ISC
11	05	64	060742.3	28.24*08	57.38*03	353	072*07	4.9BCGS	067	01.40	A	BCI
23	07	65	212932.3	25.70*11	65.33*10	710	C019*00	4.8BISC	024	02.47	B	ISC
30	07	65	190706.7	27.90*12	57.12*07	353	074*13	4.8BISC	038	02.10	B	ISC
13	11	65	061426.2	26.14*14	65.16*10	710	C033*00	5.2BEDR	019	02.36	B	EDR
13	01	66	034147.	27.60*12	57.23*05	353	084*10	0.0	020	01.31	B	ISC
09	07	66	170152.	28.20*23	57.00*16	353	047*28	0.0	022	04.04	D	ISC
22	08	66	212831.	25.10*44	61.8 *22	353	C033*00	4.7BISC	013	04.29	D	ISC
29	10	66	085938.3	27.60*03	65.68*03	710	047*01	4.9BISC	076	01.41	A	ISC
25	03	67	222627.4	28.57*07	60.36*06	353	036*09	4.9BISC	026	01.38	B	ISC
27	04	67	204747.0	26.80*13	57.99*08	353	019*24	0.0	030	02.13	B	ISC
28	04	67	193831.0	27.93*10	57.31*08	353	054*15	4.5BISC	076	03.12	B	ISC
07	06	67	223517.0	27.03*11	58.05*07	353	036*13	4.4BCGS	034	01.86	B	ISC
14	09	67	144947.0	28.40*	57.04*	353	077*	4.7BCGS	075	.		ISC
02	08	68	133023.3	27.54*02	60.92*02	353	065*04	5.7BISC	168	01.00	A	ISC
03	08	68	140140.7	25.19*05	62.87*04	354	029*01	4.7BISC	077	01.73	A	ISC
09	09	68	024618.	28.40*08	65.00*05	354	002*23	4.1 QUE	010	00.98	C	ISC
08	10	68	220544.5	27.99*05	65.56*09	710	066*14	0.0	010	01.54	C	ISC

Table 1 (*cont.*)

13	02	69	111125.1	24.99*03	62.75*02	356	027*01	5.2SMOS	069	00.95	A	ISC
01	06	69	123630.2	26.66*06	60.52*04	353	050*08	4.6BISC	023	01.01	B	ISC
04	06	69	162134.7	25.50*10	61.13*07	353	019*18	4.6BISC	034	01.68	C	ISC
21	06	69	163508.6	27.48*03	57.52*02	353	064*05	5.2BISC	154	01.12	A	ISC
20	07	69	223732.0	28.26*08	57.55*06	353	071*11	4.6BISC	050	01.95	B	ISC
07	11	69	183404.3	27.80*02	60.02*02	353	074*05	6.5SMOS	249	01.34	A	ISC
03	12	69	023149.0	24.88*06	65.56*07	356	C033*00	5.0SMOS	061	02.42	B	ISC
19	01	70	203159.5	25.30*16	61.34*11	353	C033*00	4.4BNEI	012	02.25	C	ISC
06	03	70	194007.0	28.25*05	57.43*04	353	071*07	4.6BISC	048	01.27	A	ISC
10	03	70	220625.0	28.20*13	57.38*06	353	075*08	4.4BISC	015	01.23	B	ISC
12	05	70	235912.0	27.27*09	57.21*04	353	044*09	4.7BISC	032	01.15	B	ISC
08	09	70	124513.0	28.57*07	58.85*06	353	080*13	4.7BISC	034	01.67	B	ISC
26	12	70	195205.0	27.77*06	57.88*03	353	088*06	4.8BISC	058	01.11	A	ISC
28	01	71	060930.7	28.27*05	57.29*03	353	078*06	4.7BISC	054	01.03	A	ISC
14	08	71	221558.	27.20*05	64.55*10	354	080*12	5.2BISC	023	01.46	C	ISC
03	11	71	094258.2	28.58*06	57.25*03	353	102*06	4.7BISC	045	01.06	B	ISC
04	11	71	041014.1	28.17*05	57.38*03	353	060*04	0.0	012	00.56	C	ISC
05	11	71	145551.0	24.74*04	63.46*05	356	C050*00	4.9BISC	065	01.53	B	ISC
20	12	71	232743.7	28.32*06	57.19*04	353	084*08	5.0BISC	050	01.30	A	ISC
03	04	72	090718.5	28.13*02	57.17*02	353	073*04	5.0BISC	159	00.99	A	ISC
03	05	72	215255.9	28.15*14	57.42*05	353	111*10	0.0	020	01.38	B	ISC
30	06	72	174936.8	27.17*10	57.09*08	353	059*18	4.4BISC	071	03.21	C	ISC
06	08	72	011250.5	25.04*02	61.22*02	353	036*05	5.3SMOS	181	01.11	A	ISC
06	08	72	013213.	25.2 *14	60.98*08	353	C033*00	4.8BISC	035	01.25	C	ISC
08	08	72	190931.5	25.14*03	61.22*02	353	026*02	5.0SNEI	183	01.38	A	ISC
18	08	72	100305.	24.80*21	63.14*10	356	C033*00	4.3SMOS	025	02.26	C	ISC
17	11	72	090901.7	27.40*02	59.14*02	353	079*05	5.2BISC	184	01.12	A	ISC
13	01	73	141438.	25.50*04	63.83*05	354	022*40	4.7BISC	084	01.44	A	ISC
02	04	73	012714.3	27.57*05	61.67*03	353	058*07	4.7BISC	079	01.39	A	ISC
26	04	73	143005.4	27.14*02	60.83*02	353	042*05	4.8SMOS	134	01.13	A	ISC
27	04	73	160917.0	27.90*10	60.15*08	353	022*25	4.8BQUE	012	02.08	C	ISC
24	05	73	231436.2	28.10*06	57.82*04	353	050*10	4.4BISC	062	01.73	A	ISC
08	06	73	175700.0	26.54*08	61.12*06	353	C033*00	4.7SMOS	046	01.81	B	ISC
08	06	73	214955.0	26.34*08	61.03*04	353	027*15	4.4BISC	064	01.60	B	ISC
14	08	73	182416.	25.44*03	65.58*03	710	002*13	4.5SMOS	106	01.05	A	ISC
02	09	73	072316.6	24.88*04	63.21*03	356	C024*00	5.2BISC	121	01.40	A	ISC
27	10	73	095037.7	24.58*10	62.17*04	356	C033*00	4.7BISC	023	01.02	B	ISC
10	12	73	210649.8	27.60*11	57.04*06	353	030*22	4.5BISC	082	02.83	C	ISC
04	09	74	064332.	27.4 *36	62.00*07	353	C000*00	4.7BISC	011	00.95	C	ISC
15	11	74	173747.1	27.74*10	62.50*04	353	075*06	4.5BISC	024	00.81	B	ISC
10	12	74	195016.	27.91*06	65.25*06	710	054*11	4.5BISC	025	01.43	B	ISC
20	12	74	032853.	26.61*07	61.17*05	353	050*09	4.9BISC	037	01.16	B	ISC
24	12	74	094209.1	25.55*08	64.84*06	354	C033*00	4.6BISC	011	01.27	C	ISC
17	05	75	161916.6	27.61*03	57.83*03	353	066*06	4.9BISC	202	01.59	A	ISC
18	05	75	144434.9	27.54*06	57.85*04	353	076*09	4.6BISC	120	02.03	B	ISC
20	06	75	141050.6	27.77*05	58.75*02	353	097*05	4.8BISC	103	.	A	ISC
03	02	76	145416.	25.40*	63.41*		C033*00	4.6BPDE	014	.	C	PDE
07	03	76	004235.	28.10*	57.34*		060*	4.4BPDE	025	.	C	PDE
10	03	76	043917.5	28.37*	57.38*		067*	4.7BPDE	051	.	B	PDE
26	10	76	010023.1	27.18*	58.06*		065	4.6BPDE	010	.	C	PDE
06	11	76	231852.8	28.24*	57.14*		C033*00	4.8BPDE	013	.	C	PDE
13	11	76	101232.5	28.18*	57.40*		C033*00	5.0BPDE	072	.	B	PDE
07	04	77	033438.1	27.90*	57.06*		C033*00	4.9BPDE	061	.	B	PDE
03	07	77	063841.4	25.18*	60.90*		C033*00	4.6BPDE	051	.	B	PDE
13	09	77	114847.0	27.69*	59.94*		C033*00	4.7BPDE	025	.	B	PDE

1. Latitude and longitude are given in decimal degrees. The number following the * is the standard error in km.

2. Flinn-Engdahl region number.

3. Depth and standard error, both given in km. A 'C' preceding a depth means the depth was constrained at that value.

4. Magnitude type and source: A magnitude of 0.0 = undetermined

B = Body-wave magnitude
S = Surface-wave magnitude
DBN=DeBilt, Netherlands

GTR = Gutenberg and Richter (1954)
ROT = Rothé (1969)
CGS = Coast and Geodetic Survey

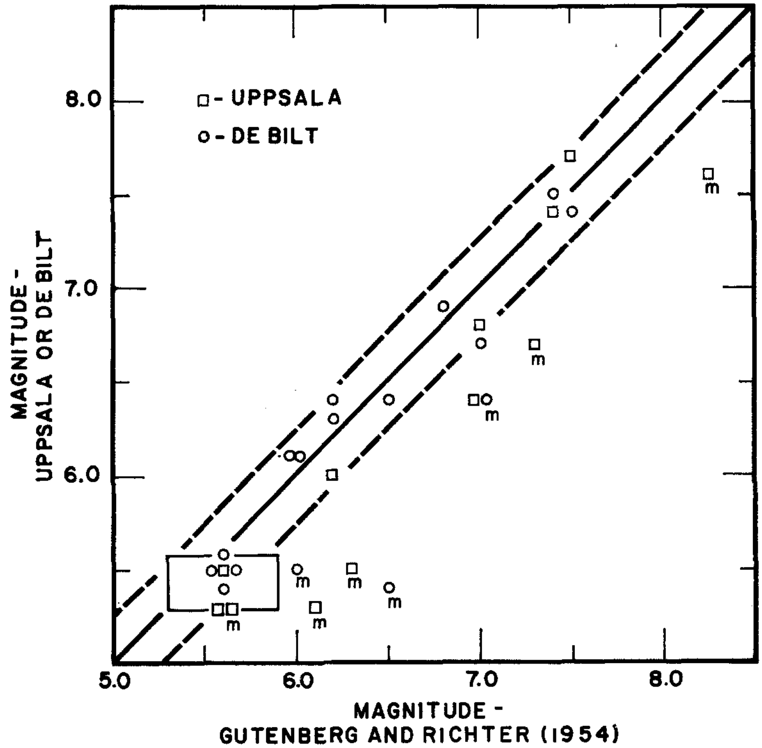

Figure 3

Comparison of surface-wave magnitudes determined by Gutenberg and Richter (1954) with those computed using ground-displacement amplitudes at Uppsala and DeBilt for earthquakes throughout south-central Asia. Those events labelled 'm' occurred in the Makran region of southern Pakistan and average about 0.6 magnitude units below the line signifying equality between the two methods of magnitude determination. The box in the lower left-hand corner represents the fact that Gutenburg and Richter used a single designation (Class d) for all earthquakes in the magnitude range 5.3–5.9.

(Notes to Table 1 continued)

MOS = Moscow, USSR
QUE = Quetta, Pakistan
UPP = Uppsala, Sweden
GGK = Geller and Kanamori (1977)

EDR = Earthquake Data Report
ISC = International Seismic Center
NEI = National Earthquake Information Center
PDE = Preliminary Determination of Epicenters

5. Number of recorded arrivals given a weight greater than 0.4 in the location.
6. Qualitative grade: A = Good, B = Fair, C = Poor, D = Very Poor.
7. Source of Data:

ISS = International Seismological Summary
BCI = Bureau Central International de Sèismologie
EDR = Earthquake Data Reports
ISC = International Seismological Centre
PDE = Preliminary Determination of Epicenters

station data to compute magnitudes for earthquakes from the Makran region results in consistently lower magnitudes relative to those determined by GUTENBERG and RICHTER (1954). The average difference between the magnitudes found by Gutenberg and Richter and those computed from Uppsala and DeBilt station data for Makran earthquakes is about 0.6 (Fig. 3). Thus, in this study, a factor of 0.6 is added to all magnitudes determined from the Uppsala and DeBilt station data.

Qualitative terms used in this paper to denote different magnitude ranges are listed in Table 2.

Table 2

Term denoting earthquake size	Associated magnitude range
Great	$M \geq 7.8$
Major	$7.0 \leq M < 7.8$
Large	$M \geq 7.0$
Moderate	$6.0 \leq M < 7.0$
Small	$M < 6$

The Makran earthquake of 1945

Teleseismic activity in the Makran region, both before and after 1945, is probably related to the occurrence of the great earthquake along the Makran coast on 27 November 1945. To examine this possibility the seismic activity is discussed here for four different time periods: (1) activity more than about 10 years before the main shock, (2) less than about 10 years before the main shock, (3) the main shock itself and the eight years immediately following it (i.e. the long-term aftershock period), and (4) the period subsequent to the decline in long-term aftershock activity.

During the first stage of activity, more than 10 years before the 1945 event, a number of moderate to large earthquakes occurred in the area located between the future rupture zone and the volcanic arc (Fig. 4A). GUTENBERG and RICHTER (1954) used depth phases and or the relative amplitudes of body and surface waves to assign depths of 80 to 110 km to the three largest of these events (in 1927, 1929 and 1934). Although original seismograms were not available to confirm the depths they determined, recent seismicity suggests the depths are essentially correct. Based upon the configuration of the slab as inferred from seismicity to the west (JACOB and QUITTMEYER, 1979), and the locations of the three events relative to the tectonic components of the subduction zone, depths of 80 to 110 km would place these events near the down-dip limit of seismic activity within the subducted slab.

Two other earthquakes of moderate magnitude occurred inland from the coast during this first stage of activity (in 1919 and 1936). Depths for these events are not known. In the discussion that follows it will be assumed that they occurred within the subducted slab.

Earthquakes of moderate to large magnitude that are located at subcrustal depths occur infrequently in the Makran region. Only seven earthquakes that are possibly of this type have been located there since 1914. (One of these shocks, which occurred in 1914, has its epicenter at 29.7°N, 63.8°E and is thus not shown in Fig. 4A.) Of these seven earthquakes, six occurred between 1914 and 1936. While not enough data exist to make a meaningful statistical analysis, the fact that only one other event of similar depth and magnitude has occurred in the entire Makran region in the 40+ years since 1936, suggests the activity prior to 1936 may not be random in nature but rather related to the preparation of the region for the great earthquake of 1945.

The activity within the subducted slab observed here is to some extent similar to a pattern discussed by MOGI (1973) for the Kurile–Kamchatka and Japanese arcs. Both sets of data are characterized by a relatively high level of moderate to large earthquakes at subcrustal depths in the years before a large, shallow earthquake. Beyond this overall similarity, however, there are many differences in the details of the observations. Mogi found a significant increase in the number of moderate to large earthquakes that occurred at depths greater than 150 km in the down-dip portion of the slab perpendicular to the impending rupture zone. The increase he observed began about five years before the associated main shock. In the Makran region it cannot be established whether the activity between 1914 and 1936 represents an increase in the level at which subcrustal earthquakes occur (since data prior to 1914 do not exist), but the rate of occurrence was certainly higher then than at any subsequent time. The level of activity is also high relative to the region west of longitude 61°E (Fig. 41A). This western region is apparently similar in its tectonics to the region associated with the 1945 earthquake (FARHOUDI and KARIG, 1977; PAGE *et al.*, 1978). It is difficult to see how unperceived changes in the tectonic regime or gradual changes in the rate of convergence could cause the abrupt change in the style of seismicity to the west of about 61°E longitude. If it is assumed that the relatively high level of subcrustal activity between 1914 and 1936 represents an increase in the rate of occurrence of such earthquakes, then the time scale over which the increase in activity is observed (30 or more to 10 years before the main event) is significantly different from that observed by Mogi (approximately five years before the main event). This difference may not be entirely unexpected in light of the other differences in the subduction process operating in these two regions. In the Makran the deepest shocks are located at depths of 80 to 100 km and are characterized by down-dip tension, while in the cases studied by Mogi the shocks occur at depths greater than 150 km and exhibit down-dip compression. Also, the large sediment accumulation in the Makran subduction zone may play a role in determining the time-scale over which "precursory" activity may be observed. Thus, if the pattern observed by Mogi and the seismicity seen in the Makran are both manifestations within the subcrustal portion of the subducted slab of the preparation of a shallow rupture zone, the manner in which the preparation of the shallow zone is manifested at depth differs in the two cases.

In the above discussion it was assumed that the moderate to large earthquakes

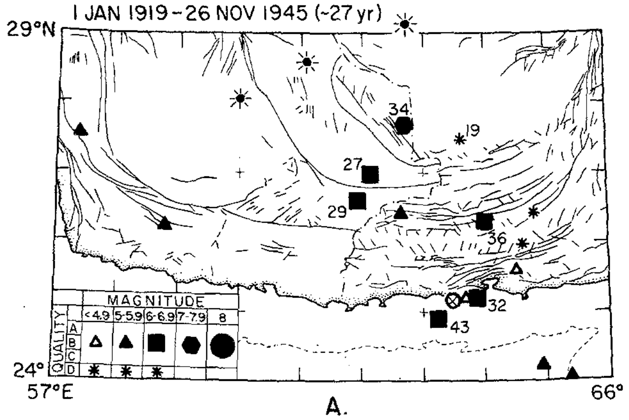

Figure 4a

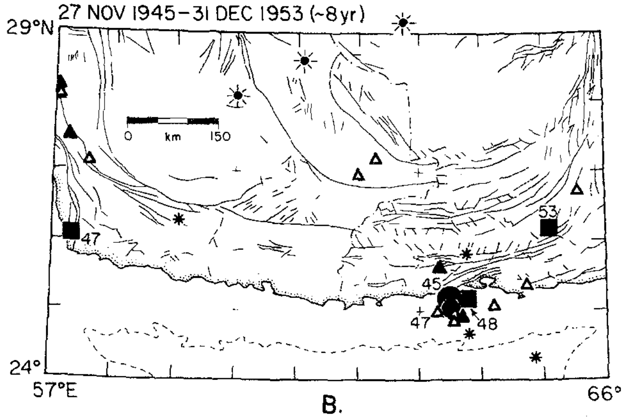

Figure 4b

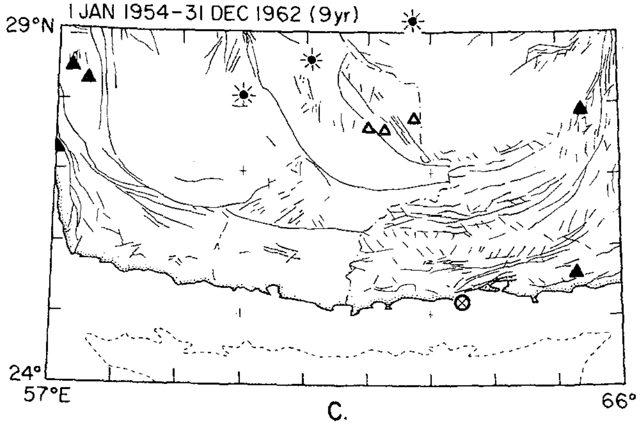

Figure 4c

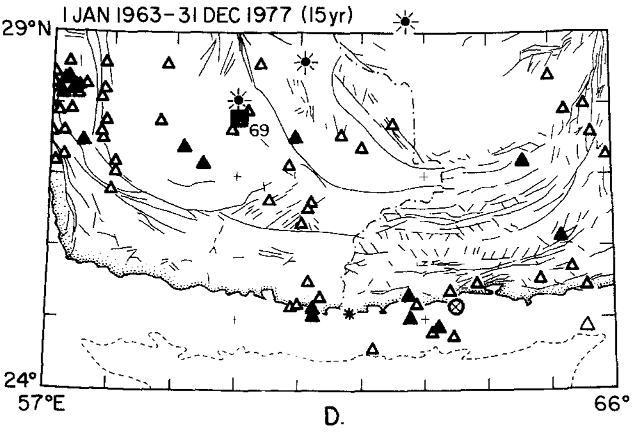

Figure 4d

Figure 4

Seismicity of the Makran region during different time periods. The magnitude-quality scale (note: there is no differentiation among A, B, and C quality events) is shown in part A; the distance scale is shown in part B. Events for which a magnitude could not be determined are plotted as if they had a magnitude of < 4.9. No differentiation is made between body- and surface-wave magnitudes (see Table 1 for this information). The epicenter of the great earthquake in 1945 is represented by a cross enclosed in a circle in parts A, C, and D. The major centers of Quaternary volcanism are indicated by filled circles surrounded by radiating line segments. The year in which earthquakes with magnitudes of 6.0 or greater occurred is indicated near the symbol for each such earthquake.

(A) Seismic activity before the 1945 earthquake. Activity is located north and northwest of the 1945 rupture zone and in the vicinity of the 1945 epicenter. The region west of this activity is relatively quiet. The two earthquakes in the southeast corner of the map are associated with the Murray ridge.

(B) The great 1945 earthquake and its long-term aftershock activity. The largest symbol (filled circle) represents the epicenter of the 1945 event. The long-term aftershock activity suggests a rupture length of 100 to 200 km to the east of the main shock epicenter. The region northwest of the rupture zone is now relatively quiet; the region west of the rupture zone remains quiet.

(C) Seismicity after the decline in long-term aftershock activity. During this period of time the entire Makran region exhibits a very low level of activitiy.

(D) Recent seismicity of the Makran region. An increased number of earthquakes are detected because of the establishment of the WWSSN. Most of these events would not have been detected during an earlier time period. Activity along the coast, west of the 1945 epicenter, produces a 'donut' pattern. One earthquake of moderate magnitude, located to the northwest of the donut pattern, may be analogous to the activity that preceded the 1945 event.

occurred at subcrustal depths within the subducted slab. If this assumption is incorrect then any analogy to the pattern observed by Mogi would be invalid. The earthquakes would then be located along the edge of the over-riding Eurasian plate, and the high rate of activity might be interpreted as similar to the increase in intraplate shocks observed prior to large earthquakes that SHIMAZAKI (1976, 1978) identified for some regions of Japan. As mentioned before, though, recent seismicity suggests these earthquakes did actually occur in the subducted slab.

During the second stage of activity, starting about 10 years prior to the 1945 earthquake, seismic activity is concentrated along the coast. Figure 5 shows that while the rate of detected activity remains fairly constant, the locations of events shift to the south. This coastal activity, however, includes events with magnitudes lower than previously detected. Thus, it seems the concentration of activity along the coast is the result of both a marked decrease in activity inland and an increase in the detection capability. Note that the coastal activity is confined to the region affected by the 1945 shock; no coastal activity is located west of 63°E longitude (Fig. 4A).

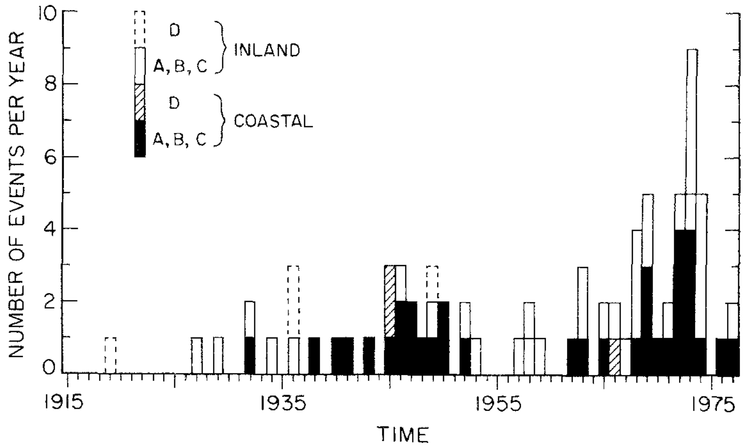

Figure 5

Number of earthquakes detected per year in the Makran region. The total column height represents earthquakes between latitudes 24° and 29°N and longitudes 59° and 66°E. The filled portion of each column represents only the coastal activity between 24° and 25.85°N. Locations of A, B, and C quality are differentiated from those of D quality. Events associated with the Murray ridge are not included. The two stages of seismic activity preceding the 1945 earthquake are easily discerned. Activity away from the coast prior to 1937 is followed by a concentration of seismicity near the coast. The decline in activity subsequent to the long-term aftershock activity is also apparent. The increase in the level of seismicity after 1965 may be almost entirely the result of the increased detection capability associated with the advent of the WWSSN. It is likely that only one or two of these events would have been detected during an earlier time period.

The activity along the coast includes two earthquakes of moderate magnitude, both of which were confined to a region within about 50 km of the 1945 epicenter (Fig. 4A). The only other earthquakes of moderate magnitude that have occurred along the Makran coast since 1915 are aftershocks of the 1945 shock or are located west of the Zendan fault system where the tectonic regime is different (Page *et al.*, 1978). The history of seismic activity along the Makran coast prior to 1945 is such that the region would have been termed a seismic gap of unknown seismic potential (category 3 in the terminology of McCann *et al.*, 1978; McCann, personal communication). Within a seismic gap some seismicity of small to major magnitude is often concentrated near the site of the epicenter of a future great earthquake and/or near the ends of the future rupture zone in the years immediately preceding the rupture

(Kelleher and Savino, 1975). The activity observed along the Makran coast during the second stage may be interpreted as activity of this type. This seismicity is therefore consistent with the patterns of seismicity observed before other large earthquakes.

In summary, seismic activity during the two stages preceding the great earthquake of 1945 is distributed over a broad zone to the north and northwest of the impending rupture and within the future rupture zone itself. Inland activity was high, relative to subsequent periods, 30 or more to 10 years before the 1945 shock. This activity decreased markedly at about the time earthquakes of moderate magnitude began to be recorded along the coast. Both activity inland and along the coast contrast with the very low level of activity to the west.

Seismicity subsequent to the Makran coast earthquake, in the eight years immediately following it (stage 3), is shown in Fig. 4B. No locatable aftershocks were recorded in the days just after the occurrence of the main shock. This may be the result of the deterioration of station operation during World War II. The activity during the next several years, however, suggests that the rupture in 1945 extended about 100 to 200 km to the east of the 1945 epicenter. The distribution of intensity values (Page *et al.*, 1978) is consistent with this conclusion. The towns of Pasni, near the epicenter, and Ormara, about 100 km to the east (Fig. 1), experienced destruction of intensity X–XI (MM); but the town of Gwadar, about 100 km to the west of the 1945 epicenter, experienced damage of only intensity V (MM).

Detected seismicity during the years after the decline in long-term aftershock activity, but before the increased detection capabilities of the mid-1960's, was very low throughout the Makran (Fig. 4C). The establishment of this state of seismic quiescence marks the fourth stage of activity; it probably reflects the release of stress associated with the 1945 earthquake. Both the rupture zone itself, and the formerly active region north and northwest of the rupture zone, exhibit almost no teleseismic activity during the period shown in Fig. 4C. The 1945 zone is now as quiet as the area to the west has been since at least 1919.

Beginning in about 1963 the number of events detected in the Makran region increases as a result of the establishment of the Worldwide Standardized Seismograph Network (WWSSN). Most of the earthquakes shown in Fig. 4D would probably not be detected during an earlier time period. Even at this lower detection limit, however, the area that was seismically active before and after the 1945 earthquake (Fig. 4A and 4B), maintains its subsequent low level of activity. This observation strengthens the conjecture that activity preceding the 1945 earthquake was in some sense related to the occurrence of that great shock; it thus represents a long-term seismic precursor.

Recent activity west of the 1945 rupture zone

Only one great earthquake along the Makran coast is documented in the historical record—the earthquake of 1945 (Quittmeyer and Jacob, 1979). Documented shocks that occurred before the advent of instrumental recording caused only minor damage over limited areas (OLDHAM, 1882; BERBERIĀN, 1976, written communication, 1978); the very low population density is not, however, conducive to the compilation of a complete historical record. Geologic evidence, on the other hand, suggests that the Makran coast, from Jask in Iran to west of Karachi in Pakistan, is episodically uplifted during great earthquakes. A series of uplifted marine terraces, found at various locations along the coast, are interpreted by PAGE *et al.* (1978) as a result of coseismic uplift similar to that which exposed a terrace at Ormara in 1945. The number of terraces appears to increase from one at Jask to nine in eastern Iran and an unknown number at Ormara in Pakistan. Even though some of the coseismic uplift will be cancelled by subsidence during the interseismic period, there appears to be a net uplift associated with at least some earthquake cycles along the entire coast. Thus, while not historically documented for the entire coast, large earthquakes probably have affected the Makran coast, from Jask to the 1945 rupture zone, a number of times in the past.

Since geologic evidence suggests the entire Makran coast is subject to large earthquakes, it is worthwhile to examine the recent seismicity in an attempt to determine where along the coast the next large earthquake might occur. Several lines of reasoning lead to the hypothesis that the region immediately to the west of the rupture zone inferred for the 1945 earthquake may be the site of the next large earthquake along the Makran coast. Recent activity along the coast west of the 1945 epicenter produces a pattern similar to the so-called "donut" pattern of MOGI (1969). A zone of relative seismic quiescence between longitudes 61.3° and 62.7°E is bounded at both ends by regions of seismic activity (Fig. 4D). This pattern is often observed prior to large earthquakes.

Northwest of the donut pattern along the coast, some earthquakes are located at depths of 60 to 80 km within the subducted slab. One of these events (in 1969) was of moderate magnitude and is thus similar to those that occurred during the first stage of activity before the 1945 earthquake. In this case, however, no other moderate to large events at subcrustal depths have yet accompanied it; thus the analogy is somewhat tentative.

Although these characteristics of the recent seismicity are consistent with an interpretation that the region west of the area affected by the 1945 earthquake along the Makran coast is preparing for a large event, the data are sparse and the arguments are necessarily speculative in nature. The geology of the region does, however, suggest that large earthquakes do occur along the entire Makran coast. In light of our present understanding of the long-term preparation of a region prior to the occurrence of a large earthquake, it would seem prudent not to dismiss the evidence simply because it is not conclusive. It can *not* be concluded that a large earthquake is imminent along the Makran coast, but the patterns observed in the recent seismicity suggest the region should be monitored in the future.

Discussion

The continuing lack of seismicity along the coast between the Zendan fault system and approximately 61°E longitude is of unknown significance. It may represent the state of activity a large number of years (>100?) before a great earthquake, whereas the recent activity east of this quiet zone along the coast may represent a more advanced stage of preparation. On the other hand, perhaps there is some unperceived change in the tectonic regime along the western portion of the Makran coast. PAGE *et al.* (1978) note that the number of earthquake-related terraces along the coast decrease towards the west, but it is difficult to see how this could be related to such an abrupt change in the seismic regime.

Future seismic activity will help to evaluate the degree of seismic hazard in the region west of the 1945 rupture zone. Moderate-magnitude earthquakes, either at depth within the subducted slab or along the appropriate portion of the coast, will strengthen an analogy to the pre-1945 activity. A lack of such activity will indicate either that such an analogy is invalid or that the first stage of activity has not, in actuality, yet begun. Similarly, smaller magnitude earthquakes may continue to define a donut shaped pattern, or this may prove to be a transitory observation.

The possibility that a large earthquake will occur along the Makran coast offers an unusual research opportunity. A large part of the preparation region for most large earthquakes occurs offshore. In the Makran region, however, the accretionary prism is subaerially exposed for most of its extent. Thus data, such as leveling measurements, can be collected in a region of interest that is often inaccessible.

Conclusions

Teleseismic activity preceding the great earthquake of 1945 along the Makran coast consists of a relatively high rate of occurrence of moderate-magnitude earthquakes at depth, probably within the subducted slab, followed by a shift of the center of activity to the vicinity of the future epicenter along the coast. This seismicity has some aspects that are similar to a pattern identified by MOGI (1973) and the activity is consistent with observations of KELLEHER and SAVINO (1975) prior to large earthquakes elsewhere around the world. The relatively high level of activity before and the low level after the 1945 earthquake suggest this activity is related to the build-up and release of stress associated with the rupture process. Geologic evidence (PAGE *et al.*, 1978) supports the contention that large earthquakes have affected the entire Makran plate boundary in the past. Activity since the early 1960's suggests the zone adjacent to that affected in 1945 may be the site of the next large earthquake in this region. The adjacent zone may have entered a stage of activity similar to that which preceded the 1945 earthquake. Small-magnitude events, which would not have been detected before the early 1960's, provide additional evidence suggesting this zone may possess a high seismic hazard; the earthquakes are distributed in space and time in a manner similar to that preceding large earthquakes in other regions of the world. The data, however, are sparse; a prediction is unquestionably *not* warranted at this time. Still, the recent seismicity along the Makran coast does exhibit some interesting characteristics, and this region should be closely watched in the years ahead.

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