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Seismotectonics and Identification of Potential Seismic Source Zones in Taiwan

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ABSTRACT

Taiwan is an active and complex tectonic region with earthquakes occurring as a response to collision between the Philippine Sea and the Eurasian plates. Furthermore, the northward subduction of the Philippine Sea plate in northern Taiwan and the eastward subduction of the Eurasian plate in southernmost Taiwan are significant seismogenic zones. Significant seismic hazards in Taiwan may either be induced by the plate boundary activities associated with lithospheric friction in the shallow part of the subduction zones at either end of Taiwan or by the intraplate activities due to plate collision. In the latter category, specially recognized as seismic sources for hazard consideration are the blind thrusts in the Western Foothills and the Coastal Plain. Similar to the 1994 Northridge earthquake, such events could be quite hazardous because the seismic sources are directly under populated urban areas. The subduction zone offshore of northern Taiwan is capable of producing M_w>7.5 events, but much of the source zone will lie offshore. The southern subduction zone extends under the Hengchun Peninsula, but the seismicity appears to be relatively low. Also to be noted are long-term seismicity patterns, such as the NW-trending belt of events between Miaoli and Puli is that extends from near the surface to depths greater than 40 km. The Longitudinal Valley faults and the Meishan fault are well known. A better understanding of the potential seismogenic structures such as the Longitudinal Valley fault system and Meishan fault may help us in proposing appropriate long term measures to mitigate seismic hazards.

(Key words: Seismotectonics, Seismic potential source zone, Seismic hazards)

1. INTRODUCTION

Seismic hazards, and the risks they pose, should be considered in the long-term planning for further industrial development and land-use. Taiwan is a tectonically complex and

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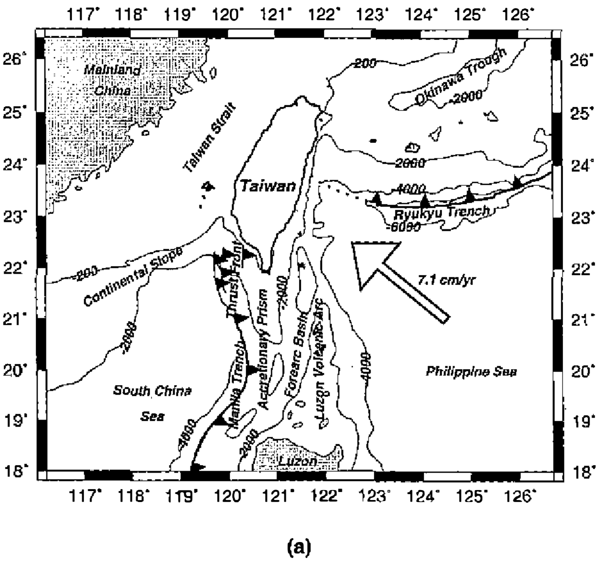
seismically very active region, consequently an area-specific identification of seismogenic structures will be useful. As our understanding of the seismotectonics of Taiwan improves, so will our knowledge of potential seismic sources. The importance of anticipating potential source structures has been elevated in the recent seismological history with a number of very damaging earthquakes that were essentially unexpected and therefore not taken into account in the design of the structures. The list of such events includes the 1971 San Fernando, the 1983 Coalinga, the 1994 Northridge and most recently the 1995 Kobe earthquakes. Damages to engineered structures resulting from these events demonstrated quite well that damages could have been lessened, if proper design measurements were incorporated. The Northridge and the Kobe events provided the necessary impetus to reexamine the potential seismic hazards from known active structures (Savage *et al.*, 1996).

The first three events mentioned above prompted the definition of the so-called "blind thrust", *i.e.*, a causative fault that does not reach the surface. Such fault may be inherently undetectable before the earthquake and is quite hazardous because it often lies under sedimentary basins where human population often concentrate (*e.g.*, Lettis *et al.*, 1997). The potential of recurrent blind thrusting in the same region can be expected once the region is known to be susceptible to such events. Knowing that the 1964 Tainan earthquake was a blind-thrust earthquake (Wu *et al.*, 1997; see below), the inclusion of blind thrusts in seismic design is a question that certainly needs to be explored in Taiwan.

On the other hand, the Nojima fault, which was found to be responsible for the 1995 Kobe earthquake, was identified before the earthquake (Toda *et al.*, 1996), but it was one among many and not considered particularly hazardous. If the Awaji island area was intensely monitored seismically for events down to magnitude 2 level, could the Nojima fault zone be identified as particularly dangerous beforehand? In Taiwan, the mapping of active faults is made difficult by the ubiquitous presence of thick Holocene sediments. Although the background seismicity has been mapped quite well, it has not been possible to associate seismogenic structures with the large historical events in western and southwestern Taiwan (Fang, 1968). The exceptions are the Meishan fault for the 1906 Chiayi earthquake and the faults activated during the 1935 Hsinchu earthquake (Bonilla, 1977). Armed with detailed seismicity in Taiwan and the knowledge that western Taiwan has been very seismically active in the last four hundred years (Fang, 1968), we can investigate potential sources based on our understanding of the tectonics of Taiwan.

In addition to intraplate seismicity of the western Taiwan, the plate boundary earthquakes should also be considered. Although there have been different interpretations concerning the subduction zones in the vicinity of Taiwan (Wu *et al.*, 1997; Shemenda *et al.*, 1992), recent seismicity mapped by the Central Weather Bureau Seismic Network (CWBSN) shows very clearly the geometry of the two subduction zones under Taiwan. It is well known that on a world-wide scale, the subduction zone events are quite often the most destructive (Kanamori, 1986). These observations led many to study the seismic risks posed by them (Kanamori and Heaton, 1996). Because the subduction zones associated with the Ryukyu and Luzon island arcs appear to terminate at the northern and southern ends of Taiwan, consequently it is not understood whether these systems pose similar hazards. We shall investigate the potential hazards of these zones in light of recent seismicity and GPS data.



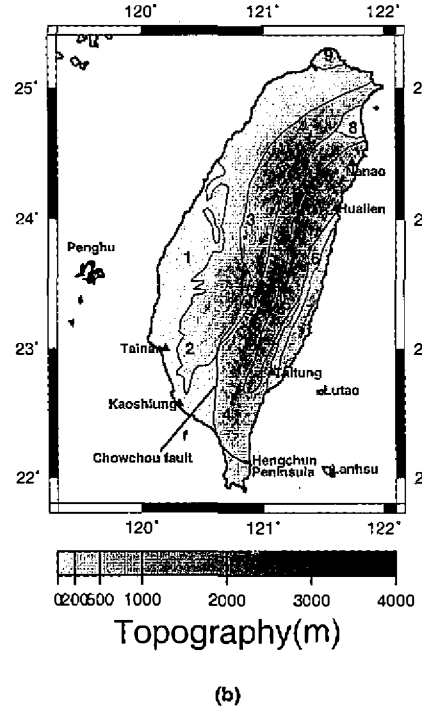


Fig. 1. (a) Overall plate tectonic environment of Taiwan (Rau and Wu, 1995). The vector of relative motion between the Philippine Sea plate and the Eurasian plate is shown by the arrow (Seno, 1977). (b) Main geologic boundaries and physiographic units (Ho, 1988): 1. Western Coastal Plain (Quaternary), 2. Western Foothills (Plio-Pleistocene), 3. Hsueshan Range (Eocene-Miocene), 4. Backbone Range (Eocene - Miocene), 5. Eastern Central Range (Pre-Tertiary), 6. Longitudinal Valley (Holocene), 7. Coastal Range (Miocene-Pleistocene), 8. Ilan Plain (Quaternary), 9. Tatun volcanic group (Pleistocene). The place names mentioned in the main body of the paper are shown in (b).

With the improved digital data now provided routinely by CWBSN, as well as geophysical data such as GPS, gravity and crustal imaging, it is possible to study and understand the tectonics of Taiwan in more detail than ever before. Not only is seismicity mapped clearly enough for us to understand the plate structures and the rheological properties of the crust, but also local earthquake tomography provides details regarding the crustal structures resulting from the effects of long-term deformation of the crust in response to tectonic stresses. In this study we use our understanding of the tectonic framework around Taiwan as a basis for deciphering the seismogenic potential of fault zones under the island.

2. TECTONIC FRAMEWORK OF TAIWAN

The main tectonic environment of Taiwan is marked by the presence of a collision orogen lying between two subduction zones as depicted in Figures 1 and 2. In Figure 1, the overall plate tectonic environment is illustrated, and in Figure 2, the interpreted plate tectonic model

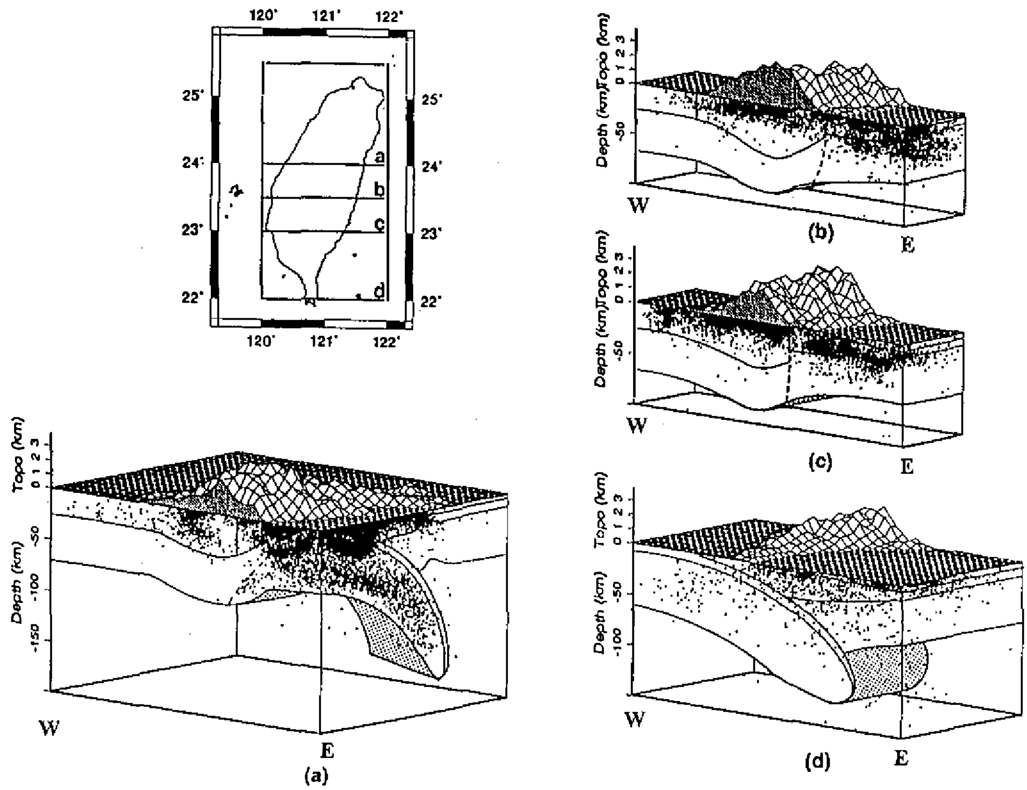


Fig. 2. Synthesis of seismological and geophysical data showing major subsurface structures. The structures are superposed on the 3-D seismic foci. The depth of the crustal features are those from Rau and Wu's (1995) seismic tomography results. The NWW motion of the Philippine Sea plate led to both northward subduction of the Philippine Sea plate (a) and the collision of the lithosphere of this plate and that of the Eurasian plate, resulting in the thickening of the crust and the lithospheres on both sides (b and c). In southern Taiwan, the Eurasian plate subducts eastward under the Philippine Sea plate (d). The locations of the blocks are shown in the index.

is superposed on seismicity (Wu *et al.*, 1997). Although the Ryukyu Trench ceases to be a bathymetric trench west of Longitude 123°E, the subduction zone complex, including the Yayaema ridge north of the trench, continues westward toward Taiwan (Lallemand *et al.*, 1997). The western edge of the shallow portion of the Ryukyu subduction zone extends westward under the eastern margin of Taiwan north of Hualien for about 20 km. The deeper part of this subduction zone extends further inland and disappears around latitude 25.3°N.

The southern subduction zone is the northward continuation of the Northern Luzon east-dipping subduction zone (*e.g.*, Cardwell *et al.*, 1980). It terminates somewhere in the vicinity

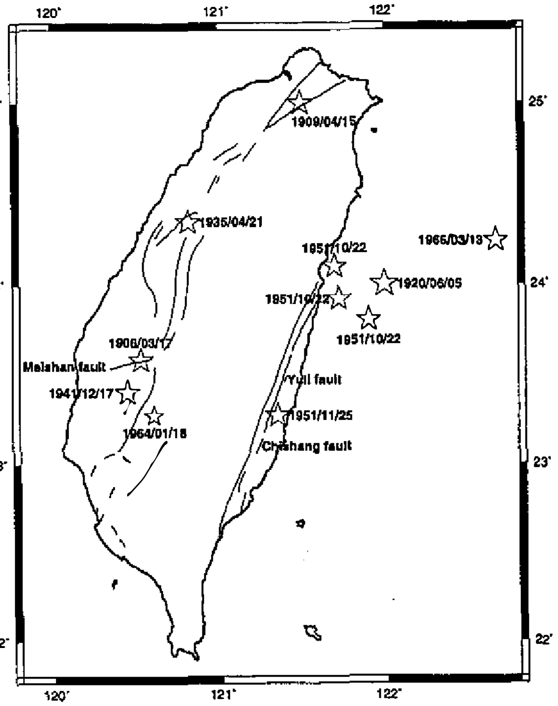


Fig. 3. Map of Taiwan showing faults that cut Quaternary deposits. Historic surface faulting shown by heavy lines (modified from Bonilla, 1977). Historical large earthquakes mentioned in the main body of the paper are shown as stars.

of a line connecting Kaoshiung and Taitung (Figure 1b). Both offshore marine geologic mapping and the geometry of the Benioff zone indicate that the southern tip of Taiwan south of this line is essentially an accretionary wedge, *i.e.*, the young sediments offshore and the young mountain onshore lie above a subduction zone. The dominant mode of deformation on the ocean floor is that of thrust faulting (Liu *et al.*, 1997). Onshore the mapping of geology is made difficult by the lack of outcrops, but the major N-S striking Chowchou fault (Figure 1b) appears to be a thrust (Ho, 1988).

The collision of the Philippine Sea plate and the Asian margin is taking place mainly in the section of Taiwan between the latitudes passing through Suao and Taitung (Figure 1b). Mountain building and crustal deformation are most active throughout this region. Many magnitude 7 or above earthquakes occurred under the Coastal Range (or just offshore of eastern Taiwan) with additional damaging earthquakes in historical time under the Western Foothills and the western Coastal Plain (Figure 3) (Fang, 1968). A particular feature of the seismicity in western Taiwan is that it is found throughout the top 40 km of the crust, in contrast to regions such as California and many other continental areas where the seismicity is mostly concentrated in the top 15 km. Within the Taiwan crust, a double-layer structure of seismicity has been identified and is evidently related to the rheology of the continental crust (Wu *et al.*, 1997). Interestingly enough, the Central Range is a seismically quiet zone, based on small earthquake data. Recent geodetic data (Liu, C.C., personal communication, 1996), however indicates that the range is rapidly rising, implying that the region is deforming in a ductile manner at depth, unaccompanied by seismic events.

3. POTENTIAL BLIND THRUSTS IN TAIWAN

The Tainan-Chiayi area has a well-documented history of seismicity (Figure 3), partly because that was the center of population since late 1600's. But with the exception of the 1906 and the 1792 earthquakes, which were apparently associated with right-lateral/normal faulting in the Meishan region, the seismogenic structures of other events are not known. No surface faulting was found for the 1941 Chiayi earthquake and based on limited first motion data (Taiwan Weather Bureau, 1942) the causative faulting could be along a blind thrust. The 1964 Tainan event, on the other hand, occurred after the establishment of the World-Wide Standard Seismographic Network (WWSSN), and had been inverted for focal mechanism (Wu *et al.*, 1997). This M_w=6.55 event has a depth of 23 km and a relatively high angle thrust mechanism. It is often thought to be related to the Chuko fault, but being at 23 km depth and not accompanied by surface faulting, it can be viewed as a typical blind-thrust event.

Judging from the fact that double seismicity layer exists in western Taiwan (Wu *et al.*, 1997), and that Taiwan is under east-west compression, blind thrusts can be expected to occur in much of western Taiwan. Blind thrusts present major problems for seismic hazard mapping, because its presence cannot be detected using surface mapping or trenching. As shown in a detailed study of the 1994 Northridge aftershocks under the Los Angeles basin, many of these thrusts do not have any associated surface expressions (Hauksson *et al.*, 1995). Even with industry-standard seismic imaging methods, which can often resolve subsurface structures down to depth of 10 km, may not be useful.

One of the main discoveries in the case of blind thrusts such as the Northridge event is that the vertical acceleration can be large (~1 g = 980 cm/s^2) for the area directly above the source. Such high acceleration usually exceeds the design criteria for many structures. For critical structures however, sufficient safeguards for such events should be considered.

4. THE NW-SE SEISMIC ZONE IN CENTRAL WESTERN TAIWAN

One of the most persistent trends of seismicity on land is the NW-trending zone stretching from Sanyi to Puli (Figure 4). It was first visible in the Taiwan Telemetered Seismographic Network (TTSN) seismicity maps (Tsai *et al.*, 1980), but it became even clearer for the CWBSN seismicity map since 1991, when the network was densified (Figure 4). It forms a nearly continuous 70 km long vertical zone with M<5 events. This group of events extends from shallow depth all the way down to about 50 km, with an interesting break around 20 km. It is one of the few well-identified continental zones that extend to such depth. Rau *et al.* (1998) studied 59 small-to-moderate-sized earthquake focal mechanisms of this area (Figure 5; Table 1). The focal mechanisms shown were determined using P first motions, SH/P amplitudes and the hypocenters relocated by 3D velocity model (see Rau *et al.*, 1996 for detailed methodology). Of the 59 mechanisms shown in Figure 5, 14 of them show strike-slip mechanisms and are consistent with the NNW-trending compression generated by collision. If the NW trend of the seismic belt represents the fault plane, then it is a dominantly left-lateral fault. There are also thrust and normal mechanisms of P axes oriented in various directions. Such a mix of mechanisms for small earthquakes is not uncommon in the vicinity of major strike-slip faults such as the San Andreas fault of California (*e.g.*, Jones, 1988). From the landforms around

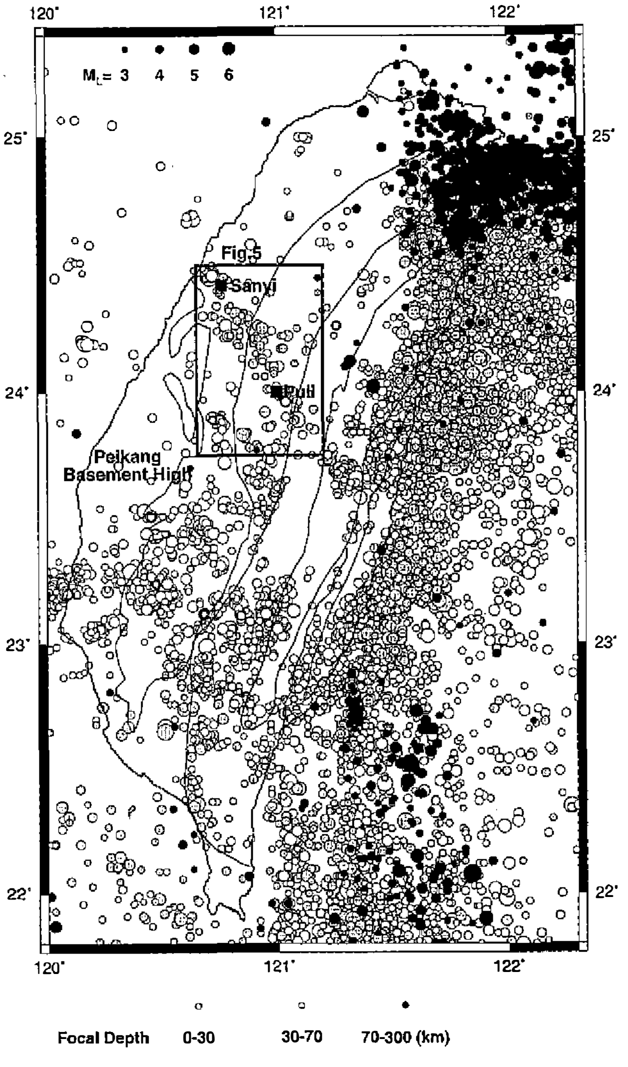


Fig. 4. Map showing 12,856 (M > 3) epicenters (circles) located by CWBSN between January 1, 1991 and December 31, 1997. The epicenters are coded for both magnitude (scale at upper left) and depth (scale at bottom in km). The main geologic divisions of Taiwan are separated by solid lines.

this fault and the direction of the collisional stress, we would expect the NW-trending seismicity to represent a left-lateral strike-slip fault with thrusting on the NE side as a result of transpression (Deffontaines *et al.*, 1994; 1997). There are geomorphic features in side-looking radar image of Taiwan that may be related to this fault (Liu and Yuan, 1982; Deffontaines *et al.*, 1994; 1997). There are also several historical events along the trend, although little evidence can be relied on for estimation of recurrence period.

The length of the fault, if activated at one time, could lead to an event comparable to that near Kobe in 1995. If activated, the direction of rupture could conceivably contribute in an important way to the damage pattern, as the northward propagation of the Nojima fault was credited with producing heavy damage in the Kobe area. For the NW zone on Taiwan, an unilateral propagation toward the southeast, in the direction of the Hsuehshan Range will

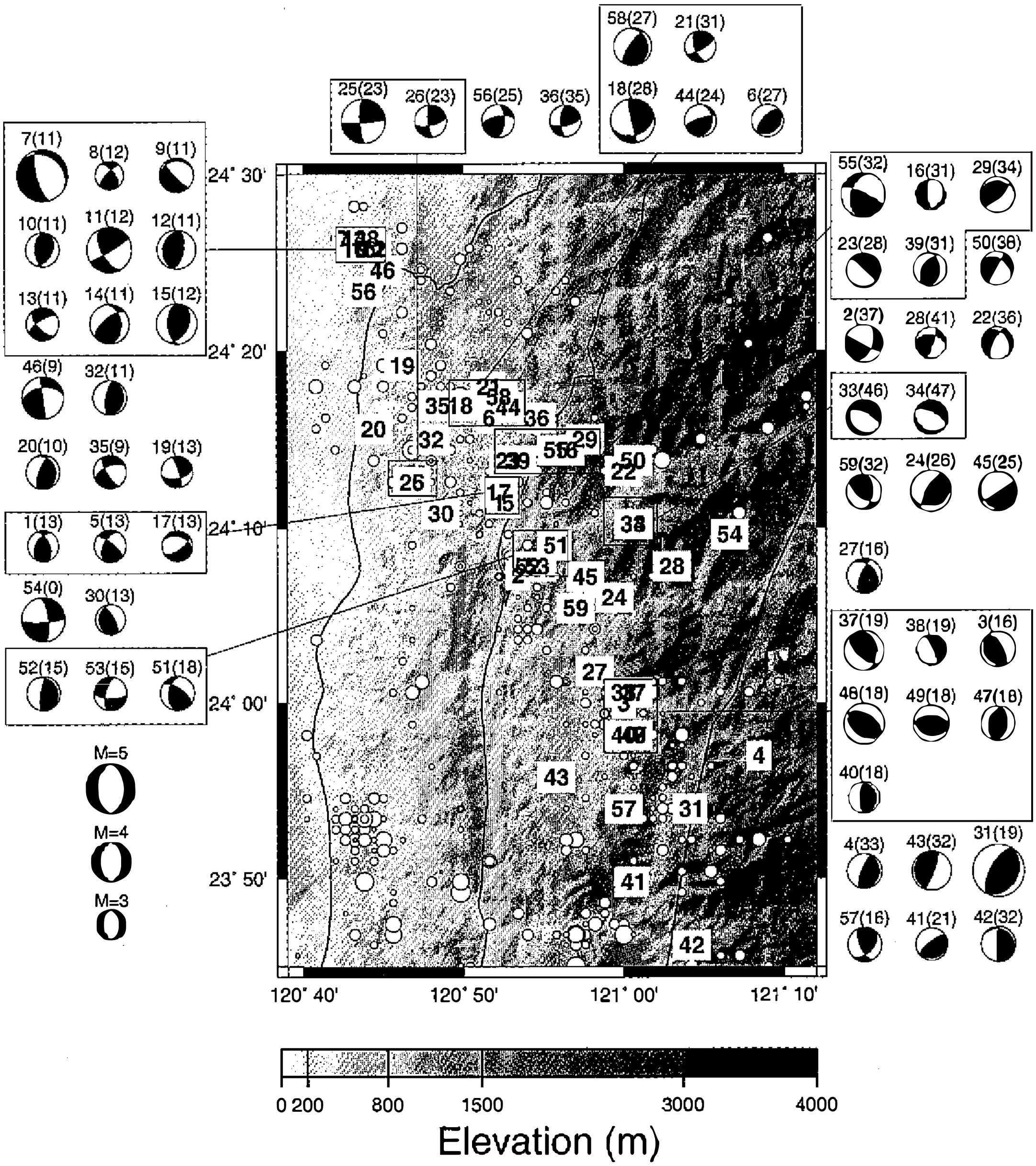


Fig. 5. Map of central-western Taiwan of which area outlined as rectangle in Figure 3 showing topography, epicenters of earthquakes, and the style of faulting of 59 selected earthquakes. Focal mechanisms are plotted in lower hemisphere; dark quadrants include compressional P-wave first motions, and open quadrants include dilatational first motions. Solutions are marked by numbers listed in Table 1 and their focal depths are shown in brackets.

Table 1. Source parameters of 59 earthquakes used in this study (SF:style of faulting).

NO	yrmoday	hrmin	lat(N)	lon(E)	depth	mag	Plane 1(s,d,r)			Plane 2(s,d,r)			P(t,p)		T(t,p)		B(t,p)		SF
1	910405	10:07	24.19	120.87	12.75	3.11	337	56	53	211	48	132	93	4	190	60	0	30	TF
2	910819	10:44	24.13	120.89	37.44	3.78	22	51	-8	118	84	-140	348	32	243	22	125	50	SS
3	910906	19:20	24	121	16.18	3.55	150	20	90	330	70	90	60	25	240	65	150	0	TF
4	911218	19:33	23.95	121.14	32.54	3.48	2	16	71	201	75	95	287	30	119	60	20	5	TF
5	920128	17:23	24.19	120.88	12.88	3.25	309	74	37	207	54	160	74	13	174	37	329	50	SS
6	920321	21:07	24.27	120.86	27.34	3.26	223	65	84	56	25	102	317	20	122	69	225	5	TF
7	920420	16:16	24.44	120.71	11.19	5.19	165	71	-74	304	25	-128	98	61	243	24	339	15	NF
8	920420	16:31	24.44	120.74	11.52	2.87	323	60	19	223	73	149	275	9	179	34	18	55	SS
9	920420	16:33	24.43	120.73	10.94	3.47	136	80	-75	258	18	-147	64	52	213	34	314	15	NF
10	920420	16:48	24.43	120.72	11.23	3.41	178	52	71	27	42	113	282	5	29	74	190	15	TF
11	920421	13:36	24.43	120.74	11.86	4.58	152	61	6	59	85	150	109	17	11	24	230	60	SS
12	920422	07:55	24.43	120.74	10.55	3.89	10	60	90	190	30	90	100	15	280	75	10	0	TF
13	920422	19:59	24.44	120.72	11.17	3.33	137	64	-24	238	68	-152	98	35	6	3	272	55	SS
14	920426	13:59	24.44	120.72	10.95	3.94	354	41	41	231	64	124	297	13	187	57	35	30	TF
15	920429	16:54	24.43	120.73	11.56	4.05	178	52	71	27	42	113	282	5	29	74	190	15	TF
16	920618	20:18	24.24	120.94	30.98	3.05	35	25	-52	175	71	-106	61	61	277	24	180	15	NF
17	920917	10:41	24.2	120.87	13.49	3.09	289	35	-42	55	67	-117	287	58	165	18	66	25	NF
18	921216	12:29	24.29	120.83	27.73	4.43	168	86	55	72	35	173	287	32	46	39	171	35	U
19	930120	20:21	24.32	120.77	12.69	3.16	342	81	-34	77	56	-170	294	30	34	17	149	55	SS
20	930203	08:35	24.26	120.74	10.49	3.38	340	25	52	201	71	106	279	24	134	61	15	15	TF
21	930327	14:08	24.3	120.86	31.01	3.19	159	59	16	60	76	148	113	11	16	33	220	55	SS
22	930504	11:16	24.22	121	36.06	3.28	205	69	-58	325	38	-144	156	54	271	17	12	30	NF
23	930602	10:58	24.23	120.88	28.21	3.43	313	85	-80	69	11	-154	234	49	34	39	132	10	U
24	930810	15:24	24.1	120.99	25.92	4.1	210	71	69	80	28	137	316	23	91	58	217	20	TF
25	931213	09:23	24.21	120.78	23.4	4.46	177	76	5	86	85	166	132	6	41	14	246	75	SS
26	931213	09:25	24.21	120.78	22.69	3.22	172	76	21	76	70	165	303	4	35	25	204	65	SS
27	940621	23:54	24.03	120.97	15.99	3.55	318	36	31	202	73	122	268	21	149	52	12	30	TF
28	940629	03:26	24.13	121.05	41.29	3.16	18	79	44	277	47	165	140	21	247	36	28	45	SS
29	950418	18:38	24.25	120.96	33.64	3.56	47	75	74	275	21	136	150	29	297	57	51	15	TF
30	950420	13:56	24.18	120.81	12.98	3.03	331	70	79	180	22	117	69	25	224	63	335	10	TF
31	950707	03:04	23.9	121.07	19.23	5.3	30	25	90	210	65	90	300	20	120	70	30	0	TF
32	951115	04:20	24.25	120.8	10.96	3.43	10	20	90	190	70	90	280	25	100	65	10	0	TF
33	951115	17:47	24.17	121.01	45.58	3.51	139	26	-67	294	65	-100	184	68	33	20	299	10	NF
34	951115	19:07	24.17	121.01	46.86	3.45	295	65	-90	115	25	-90	205	70	25	20	115	0	NF
35	951201	03:13	24.29	120.82	8.65	3.29	148	75	-32	247	59	-163	103	33	201	11	307	55	SS
36	960102	16:53	24.27	120.91	34.7	3.15	180	66	26	79	66	154	129	0	39	35	219	55	SS
37	960330	10:53	24.01	121.01	19.26	4	131	61	67	353	35	126	236	14	1	65	143	20	TF
38	960330	12:17	24.01	121	19.48	3.06	335	80	-84	128	11	-117	252	55	61	35	155	5	NF
39	960417	08:43	24.23	120.89	30.95	3.32	3	42	67	213	51	109	289	5	182	74	20	15	TF
40	960418	21:10	23.97	121	17.5	3.15	349	25	78	182	65	95	268	20	103	69	0	5	TF
41	960531	10:55	23.83	121.01	21.09	3.25	233	75	84	73	16	109	328	30	136	60	235	5	TF
42	960611	10:01	23.75	121.07	31.62	3.54	304	17	33	182	80	105	260	34	110	52	360	15	TF
43	960615	21:10	23.93	120.93	32.37	3.94	173	11	63	21	80	95	106	35	397	55	200	5	TF
44	960811	09:42	24.28	120.88	24.29	3.2	8	28	29	253	76	116	323	27	193	51	66	25	TF
45	960815	04:20	24.12	120.96	24.65	3.86	236	90	75	146	15	-180	341	43	132	43	236	15	U
46	970520	14:55	24.41	120.75	9.33	4.26	352	90	40	262	50	180	119	27	225	27	352	50	U
47	970523	10:23	23.97	121.01	17.69	3.47	5	45	83	195	45	97	280	0	190	85	10	5	TF
48	970528	11:54	23.97	121.01	18.01	4.08	300	50	83	131	40	98	35	5	170	83	305	5	TF
49	970526	16:37	23.97	121.01	18.12	3.61	271	55	83	102	35	96	6	10	158	79	275	5	TF
50	970607	03:38	24.23	121.01	37.67	3.35	209	86	-49	304	40	-174	153	36	268	29	26	40	U
51	970709	12:31	24.15	120.93	17.89	3.45	305	65	51	188	45	144	62	12	168	52	323	35	TF
52	970719	21:17	24.13	120.9	14.82	3.39	332	17	55	188	75	100	269	29	112	58	5	10	TF
53	970802	20:18	24.13	120.91	14.72	3.31	91	68	-28	193	64	-156	51	35	143	3	237	55	SS
54	970804	12:59	24.16	121.11	0	4.43	353	72	-10	87	80	-162	311	19	219	5	115	70	SS
55	970820	07:03	24.24	120.93	32.03	4.4	294	82	49	196	41	166	55	26	168	39	301	40	U
56	971022	21:45	24.39	120.73	24.6	3.32	4	60	28	260	65	147	313	3	220	40	47	50	TS
57	971115	11:45	23.9	121	15.98	3.45	156	67	45	45	48	149	276	11	19	48	177	40	TS
58	971126	17:57	24.29	120.87	26.99	3.77	346	21	44	215	75	105	292	29	145	57	31	15	TF
59	971223	16:46	24.09	120.95	22.83	3.56	124	61	49	6	48	141	242	8	343	54	146	35	TF

result in less damage for cities near the coast than if the propagation direction is reversed.

It should be remarked that this fault appears to be the northern border of the Peikang basement high on the Chinese continental margin (Figure 4). There is another belt of concentrated seismicity on the southern side of the basement high, which includes the region of the 1906 Chiayi event. These bounding faults may be important seismogenic structures as the Peikang basement high seems to be an aseismic zone, therefore relatively undeformed compared to its surrounding areas.

5. SUBDUCTION ZONES

As shown in Figure 2 the northern and southern subduction zones are rather clearly defined by the inclined seismic zones. Both subduction zones terminate under Taiwan; the northern zone is part of the Ryukyu system and the southern zone lies along the Northern Luzon-Taiwan arc system. The Philippine Sea plate is moving relative to the Asian plate at about 7 cm/yr in the direction of N55°W (Seno, 1977). Thus the N70°W direction of the northern Taiwan results in a down-dip subduction velocity of only ~2 cm/yr; the Philippine Sea plate moves at a velocity of about 6.5 cm/yr perpendicular to the trend of Taiwan, leading to the Taiwan orogeny. With the relatively small down-dip velocity, it is surprising to see a very active zone. Using the western portion of the Aleutian seismic zone as an analog one would expect a westward decrease both in seismicity and in the depth of the Benioff zone. Such is not the case for the seismic zone offshore of northern Taiwan. Ryukyu Trench is prominent along the length of the Ryukyu arc but it disappears near 123°E longitude. The E-W trending Yayaema ridge, the forearc of the subduction system, is well-developed except next to Taiwan where several N-S features related to the collision of Taiwan truncates the ridge. This subduction system has produced many earthquakes, with the 1920 M_S=8 event (Figure 3) being the most notable.

The southern Taiwan seismic zone terminates in the vicinity of 23°N latitude against the collision complex of Central Taiwan. Above this zone is the accretionary wedge, of which the Hengchun Peninsula is a part (Figure 1); it is clearly mapped in two marine geophysical studies, the 1990 MW9006 cruise of R/V (Lundberg *et al.*, 1992; Liu *et al.*, 1992) and the 1995 Ocean Research 1/Ewing (Liu *et al.*, personal communication, 1996). The Northern Luzon subduction system as a whole is not as seismically active as the Ryukyu system offshore of northeastern Taiwan. While the Manila Trench has been mapped clearly up to 21°N (Liu *et al.*, 1992), and the presence of normal faulting along the trench axis up to that point makes it a well-defined system, the trench also disappears northward. However, the clear east-dipping Wadati-Benioff zone present under southern Taiwan (Figure 2) and the offshore tectonics confirm the existence of the subduction zone. The maximum depth of earthquakes in this zone reaches about 150 km, versus the more than 200 km depth of the Ryukyu zone. It is interesting to note that the seismic characteristics of the southern tip of Taiwan is very different from that of the Central Range. While the crust under the Central Range is clearly a zone of low seismicity, but at the corresponding depth under the Hengchun Peninsula, the seismicity is quite high.

Of the world's subduction zones, Kanamori (1986) recognized those that generate great shallow earthquakes that are very energetic and those do not. The subduction zones along

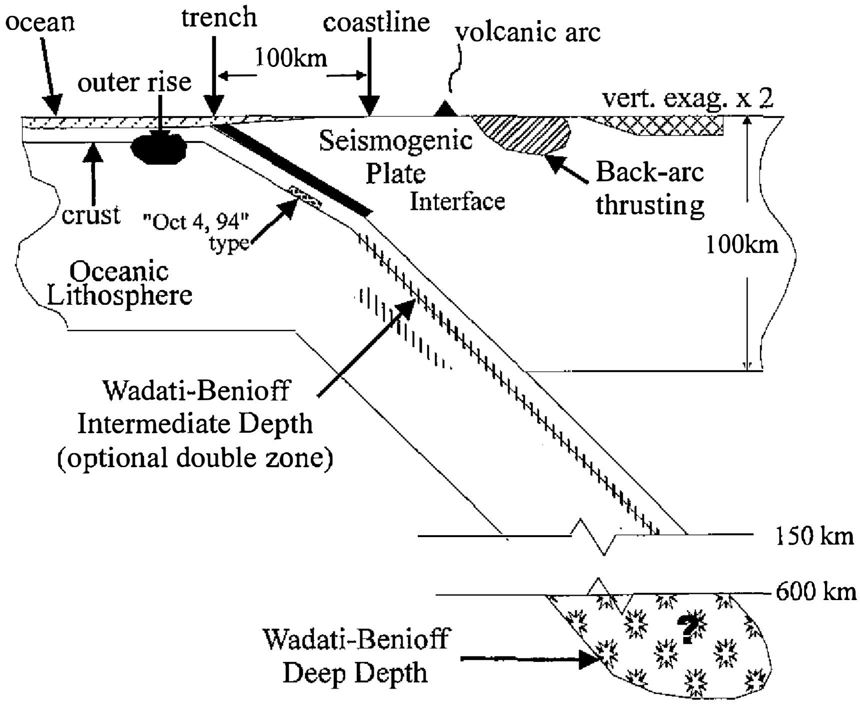


Fig. 6. The seismogenic features of a subduction system (following Ruff, 1996). The "October 4, 1994 " type refers to a M_w=8.3 event in the Kuriles that is inside the slab. However most of the "great" earthquakes in the subduction zones belong to the interface type with their locations marked by the thick line.

South American, Alaskan, Kuriles, and Japan belong to the "strongly coupled" category and are capable of generating M_w>8.5 events. Other subduction zones generate lesser events that could nevertheless be destructive when an event is close to a populated area. There is no reason to suspect that the northern and southern subduction zones of Taiwan can generate great earthquakes because of the break of the Ryukyu system by the subduction of Gagua Ridge (Schnurle *et al.*, 1998), whereby the effective length of the seismogenic zone near Taiwan is limited to apporoximately 100 km. Ruff (1996) summarized the seismogenic structures in a subduction complex as shown in Figure 6. The shallow interplate thrusts are likely to be the locus of large events. Because the depth of the zone is limited, the size of the events will be determined mainly by the horizontal rupture length. Regarding the subduction systems in Taiwan, how big can the northern subduction zone earthquake be? Figure 7 shows the 1977.1-1996.7 Harvard CMT solutions for this region. The Harvard catalog is a fairly complete one for events greater than about M_S=5.6. It can be seen that a gap exists as marked by the rectangle. With the possible length of about 110 km, it may correspond to a magnitude 7-8 event (Ruff and Kanamori, 1983). The occurrence of the 1920 event demonstrated that such size

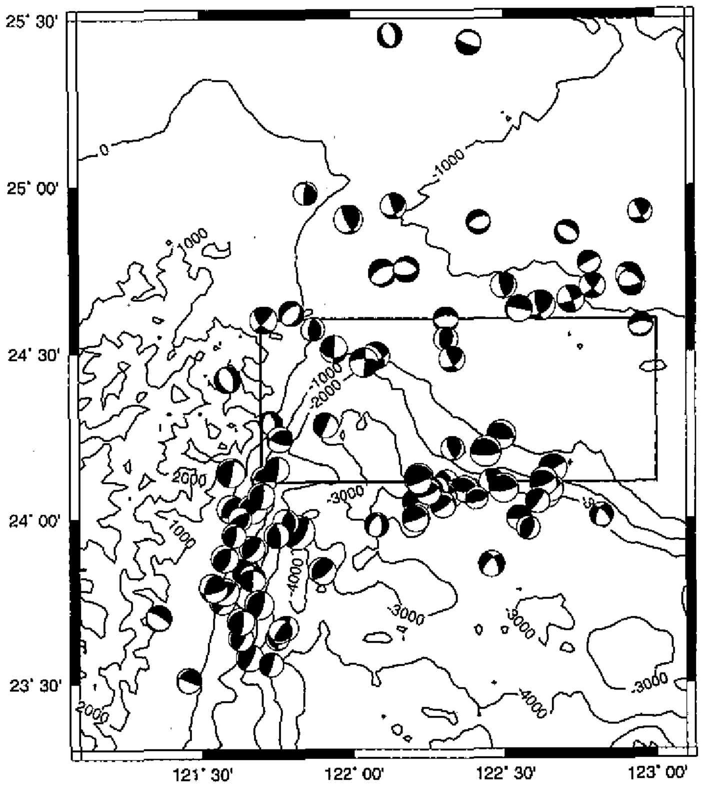


Fig. 7. Harvard CMT solutions of $M_w > 5.6$ earthquakes from January 1977 to February 1996. Note that a gap exists between the normal faulting and shallow thrust events. Could this be the rupture area for a future interplate event?

events in the area is possible. Incidentally the 1966 M_w=7.8 event (Figure 3) was actually a subduction earthquake, judging from its depth of over 50 km. Since only a small portion of the potential fault plane underlies eastern Taiwan, the potential long-distance effect to the city like Taipei is unknown. However the 1985 Mexico earthquake proved that seismic energy with periods of a few seconds can cause damages at a distance of several hundreds of kilometers and therefore such an event may generate similar effects away from the source zone.

The two subduction zones under Taiwan differ from most of the cases cited above. While most of them, with the notable exception in the case of the Alaskan zone, are in the mid-section of an elongated zone of plate convergence, the Taiwan zones are at the ends of subduction systems. Recent GPS measurements (Yu *et al.*, 1997) show that the Eurasian plate underthrusts the Philippine Sea plate in southern Taiwan at an average rate of about 4.5 cm/yr. If the release of energy is totally elastic and on one fault, then a magnitude 6.5 earthquake with a slip of 1.5 m, say, will have a recurrence rate of about 30 years. It is interesting to note that the rate of apparent relative plate motion is faster in the southern zone than in the northern zone, but the seismicity is much lower in the southern subduction zone than in the northern subduction zone. This apparent contradiction can be understood in terms of intraplate deformation of the Philippine Sea plate in the northern zone where additional motion is caused by the northward escape of the plate in the collision process (Wu, 1978).

6. LONGITUDINAL VALLEY

Based on surface geology and seismicity, the Longitudinal Valley appears to be the collision suture. It is also a major boundary separating two regions with different seismic characteristics, resulting most probably from different crustal rheology (Wu *et al.*, 1997). The series of significant earthquakes in 1951 (Figure 3) had unquestionably demonstrated this zone to be active. The average displacement for the November 25, 1951 event is determined to be 1.6 m along the Yuli fault (Hsu, 1962). A simple approach to estimate the rate is to divide this displacement by the average fault parallel rate of motion due to the relative motion in between the Philippine Sea plate and the Eurasian plate. With a rate of 2 cm/yr (Yu and Liu, 1989) the recurrence rate is 80 years. However, since the neighboring section of the Longitudinal Valley between the Meilun fault and the Yuli fault, the Chishang fault or the section south of the Chishang fault may not have broken in 1951, the occurrence of an event of M~7 in the Longitudinal Valley cannot be ruled out. The traditional view is that along an oblique converging plate boundary strain partitioning may occur. As a result, strike-slip faulting and thrust faulting would take place as separate events. Several major thrust faulting events have occurred since 1972 (Wu *et. al.*, 1989). Such events appear to be common and their magnitudes are not greater than 7.

7. DISCUSSION AND CONCLUSIONS

In this paper we have discussed the seismogenic structures of Taiwan that have either not been heretofore discussed or discussed fully, including both plate boundary and intraplate seismogenic zones. The 1906 Chiayi and the 1935 Hsinchu earthquakes in western Taiwan are well known and recurrence along the causative faults is expected. Historical records indicate that damaging earthquakes in western Taiwan recur every twenty five to thirty years, but the events may include both shallow faulting types (such as the 1906 and 1935 events) and blind thrust types under the Foothills. Because of a lack of historical record in eastern Taiwan, the recurrence rate of earthquakes on land is not known. Based on recent seismicity, however, it is widely known that eastern Taiwan is much more active than western Taiwan. It is also interesting to note that the intermediate depth events in the northern subduction zone could lead to damages as did the 1909 earthquake (Figure 3) under Taipei.

There are several ways in which the seismogenic structures discussed above can be used in practical analyses. Since these structures generate background seismicity, ground motions recorded from the events can be used as empirical Green's functions to produce ground motion models expected from a "mainshock". For general estimates one can also use world-wide accelerograms from similar structures and ground conditions to obtain estimates of ground motion.

Here in Taiwan, just as in other seismic regions, our knowledge of seismogenic structures are not yet, and probably will not be in the foreseeable future, completely known. Our attempt to circumvent this inadequacy is to base our deduction on tectonic models, which are derived from crustal structures, gravitational data, focal mechanisms, surveying, surface geology as well as seismicity. Deductions based on tectonics are therefore more general than those based on seismicity alone. It is conceivable that we shall be able to build a numerical model, incorporating constitutive relations for the materials, such as the ambient temperature and pressure, fluids as well as the stress field. A more systematic and rational view of the dynamics of the earthquake problem as a function of time can then be pursued.

The planning and execution of seismic hazard reduction procedures are long term processes. Once information is gathered on potential seismic sources, scenarios can then be constructed. The recent study on the Hayward fault in the San Francisco Bay area (Savage *et al.*, 1996), is such an example. Such scenarios can then be used as a prelude to planning a series of studies in the fault zone. It is never too early or too late to start the process. On the one hand, retrofiting structures may be effective. On the other hand, seismic designs for future major structures, bridges, tall buildings, and lifelines and the formulation of land-use policy must take these potential sources into account. It is interesting to note that after initial hazard plans having been formulated in Southern California, the focus of study has now shifted to fundamental seismological questions. For a truly useful long term plan, the input to the planning has to be on a firm basis.

The Central Weather Bureau has installed two excellent recording networks for the gathering of basic seismological data. While the CWBSN records small earthquakes, the strong motion network can record the largest events on scale to provide data needed in engineering practices as well as for studying source dynamics. On this basis many new and potentially fruitful studies can be launched. The progress in seismological studies in Taiwan was spurred onward at first by a few large damaging earthquakes, but the recent advances had been in the direction of anticipation. Such direction is inherently more desirable than otherwise.

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