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Illustrating 100 Years of Taiwan Seismicity

Chien-Ying Wang[1] and Tzay-Chyn Shin[2]

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ABSTRACT

The instrumental observation of earthquakes in Taiwan has been initiated since 1898. Up to 1997, about 170,000 earthquakes have been accumulated in the earthquake catalog. It is interesting to review this 100 year seismicity at the end of this century. In this paper, we illustrate the distributions of these earthquakes using different plotting techniques, under different categories to exhibit the nature of their occurrences. Some interesting earthquake distribution patterns are discovered, which may not be noticed before. It is no doubt that Taiwan earthquakes are stimulated by tectonic movement around the island. By ultilizing earthquake distribution figures, we attempt to relate the seismicity to the tectonics. Four seismic systems which may be drived from different tectonic interactions are taken to describe their particular seismicity patterns. Many interesting features of the tectonic movement can be explained by a careful examination of the seismicity distributions. Besides, we also hope that these well documented earthquake figures will be useful for other purposes or simply for general science education.

(Key words: Seismicity, Tectonics, Taiwan earthquakes)

1. INTRODUCTION

The distribution of earthquake hypocenters reflects abundant information on tectonic interactions, which has long been used as the fundamental input to the theory of plate tectonics. This seismicity distribution is even more significant for a neotectonic region such as Taiwan. The earthquake activity around this island is largely controlled by the current on-going tectonic movement (Tsai, 1986; Yeh *et al.*, 1991). In this paper, we attempt to use the 100 years of recorded seismicity data to describe the distribution of Taiwan earthquakes and to discuss its relationship with the surrounding tectonics. By ultilizing specially designed trajectory projections, we may examine the seismicity from different viewpoints, and obtain a deeper understanding on the occurrence of Taiwan's earthquakes.

[1]Institute of Geophysics, National Central University, Chungli, Taiwan, ROC
[2]Central Weather Bureau, Taipei, Taiwan, ROC

Taiwan is located in an active curved collision belt which developed as the result of the late Cenozoic oblique collision between the Philippine Sea plate and the Eurasian plate (Suppe, 1984; Barrier, 1986; Ho, 1986; Angelier *et al.*, 1990; Teng, 1990; Huang *et al.*, 1992; Lu and Hsu, 1992). There are three existing tectonic systems around Taiwan (Hu, *et al.*, 1997). The Penglai orogeny, which started about 6 million years ago, is still the most prevalent tectonic force acting on the island. In the Penglai orogeny, the Philippine Sea Plate (PSP) carries the mass of the Coastal Mountain Range (island arc) and collides with the passive Eurasian continental margin at an oblique angle (Seno, 1977; Ho, 1986). The PSP subducts northward offshore northeastern Taiwan after the collision. This collision has built up the Central Mountain Range as the metamorphic core of Taiwan island and created many thrusts and folds in the western sedimentary foothills. The movement has also pushed the old South China Sea (SCS) plate system, which was dominant during the Miocence time (30 million years ago) with the subduction along the Manila trench toward the east, to retreat toward the southwestern (Teng, 1992). Since early Tertiary time (50 million years ago), an extension system proceeding from Mainland China has created a sequence of half grabens in the Taiwan Strait (Sun, 1985; Wang, 1987), which have cracked the crust erupting basaltic lava to form the Penghu island. This extension system has developed the Pei-Kang basement High (PKH) in the middle of western Taiwan, which latter acts as a barrier to block the PSP's movement. Thus we have three systems: the PSP in the east, the SCS in the south, and the PKH in the west. Most Taiwan earthquakes occur under the framework of interactions between these three systems. In the following sections, we will use seismicity patterns to further describe this tectonic interaction.

2. TAIWAN EARTHQUAKE OBSERVATION HISTORY

Many earthquakes occur in the Taiwan area. The numbers of earthquakes are about 1500 (M>3), 220 (M>4), 24 (M>5), and 1.3 (M>6) annually. The history of Taiwan earthquake observation started quite early, from the beginning of this century up to the present. This one hundred years of observation history can be divided into four periods. The first, from 1898 to1945, is the period of Japanese occupation. Similar to the Japanese system, the obligation of earthquake observation was then assigned to the Taiwan Meteorological Observatory (today's Central Weather Bureau, CWB). During this period, earthquake observatories were installed within the weather stations including today's Taipei, Hsinchu, Taichung, Tainan, Kaohsiung, Hengchung, Tawu, Taitung, Hsinkong, Hualien, Ilan, Alishan, Yushan, Penghu, and Lanyu. There were then a total of 15 stations equipped with Gray-Milne, Wiechert, and Omori seismographs at different times (Hsu, 1961).

The second period, from 1946 to 1972, was a period of depression for Taiwan earthquake observation. Due to the decay of Japanese instruments and the economic difficulty of the postwar time, the official earthquake observation was sustained by the CWB to only a limited degree. Fortunately a WWSSN station ANP was installed at Mt. Tatun in 1963, which represents a minor improvement on observational activity during this period. The third period, from 1973 to 1990, saw the founding of an earthquake research group under the National Science Council in 1971, which has become today's Institute of Earth Sciences (IES), Academia Sinica. The IES deployed a new generation earthquake observation network throughout the island, called the Taiwan Telemetered Seismic Network (TTSN). The TTSN has 25 stations with each station name initialized with 'TW', which are located mostly in mountain areas. The signals are sent through telephone lines to Taipei for central recording. With good site locations and central recording, the TTSN can record many small earthquakes (M<4) and begins to accurately portray the seismotectonic features around Taiwan (Tsai *et al.*, 1977; Wu, 1978). This period, called the TTSN period, establishes a firm basis for Taiwan earthquake observation.

The fourth period goes from 1991 until now. The instruments of the old CWB seismic network have been gradually upgraded since 1981. In 1986, two big earthquakes, offshore Hualien, have caused some damage in Taipei city, the capital of Taiwan. This event has pushed the government to develop a modern earthquake watching system. A new telephone line connecting seismic network of 75 stations is formed, which includes the old CWB stations (19), the TTSN (25), and some newly installed stations (31). Among them, seven stations located within the city have buried sensors in deep wells (> 200 m). The new system is called the Central Weather Bureau Seismic Network (CWBSN) (Figure 1). The CWBSN uses 3-component S-13 seismometers (a Teledyne product) which have enough sensitivity to record many small earthquakes. By using widespread stations and modern instruments, the accuracy of earthquake's location determined by the CWBSN can be constrained to within 2 km inland and 5 km offshore. Besides the CWBSN, the CWB also deploys 600 accelerometers (A900, A800, and IDS) over the populated area of Taiwan to collect strong motion data (called Taiwan Strong Motion Instrumentation Program, TSMIP). Every CWBSN telemetered station is also equipped with an A900, among which 52 stations have FBA output, sending continuous signals to the center to aid the CWBSN. The CWBSN records over 12,000 earthquakes every year, which is double or triple the number of those recorded previously.

Figure 2 plots earthquakes recorded during different periods. The smallest earthquake in the catalog has a magnitude of 1.1 and the largest 8.3. Only large earthquakes (M>4) were reported during the first period (1898-1945) and the second period (1946-1972). Due to the limited hypocenter determination ability at that time, many earthquake locations were merely assigned within a 10km x 10km grid. Hence, except when discussing M>6 earthquakes, we shall avoid using these data as much as possible. Great improvements began during the third period (1973-1990). Much higher fractions of seismicity was recorded in this period, at least 4000 earthquakes every year. The tectonic pattern in the Taiwan area was recognized shortly after the TTSN data began to come in, and this pattern has not changed much since then. The recorded seismicity by the modern CWBSN (1991-1997), however, has increased even more rapidly. Many interesting seismicity patterns especially on land stand out (Figure 2). By using the modern CWBSN data, we can examine the Taiwan earthquakes in great detail. Comparing the different plots in Figure 2, we may obtain better understanding of the recording ability and earthquake pattern changes in different time periods.

Figure 3 shows the annual earthquake number for different magnitudes in the past 100 years. In this figure, 3(d) gives the energy release calculated by the Gutenburg-Richter relation: $\mathrm{Log(E)}=11.8+1.5M$, where M is the magnitude. The data seems quite random, and there does not exist a simple rule for the earthquake recurrence rate. However, the long-term average appears to be stable. It is apparent that the reported numbers of earthquake depend on the

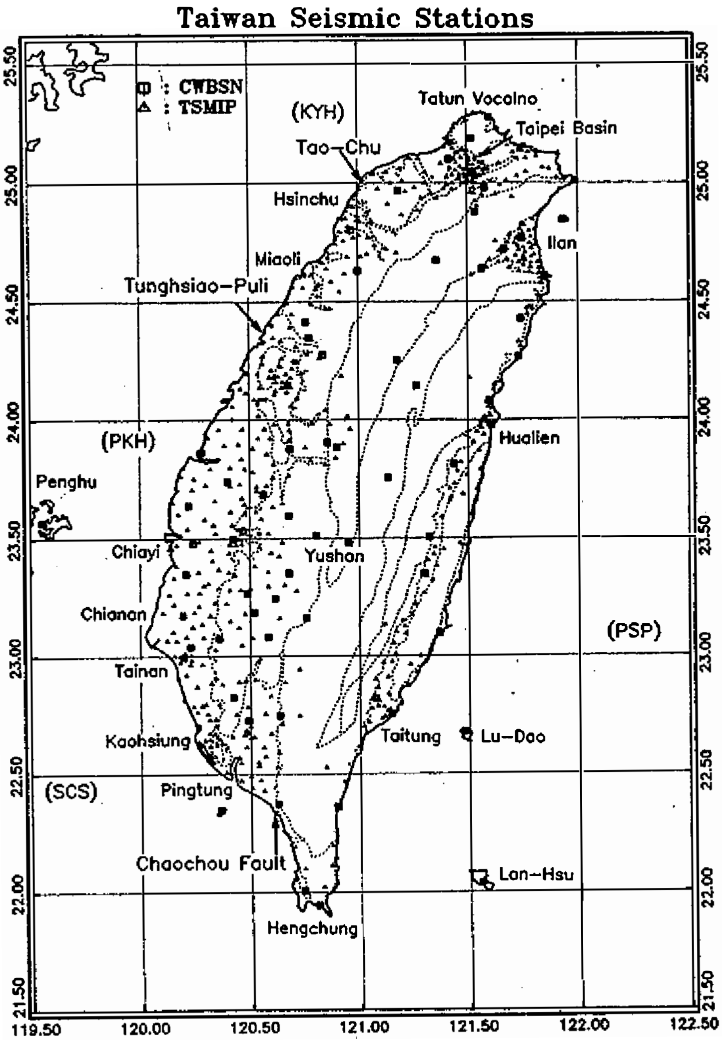


Fig. 1. Taiwan earthquake observation network (CWBSN) and the strong motion station (TSMIP). The CWBSN has 75 stations deployed over the Taiwan island and the surrounding islets. Every CWBSN station is equipped with a three-component S-13 seismometer, which sends continuous digital data to Taipei Center through the telephone lines. In addition, every CWBSN station also has an A-900 accelerometer (as a TSMIP station). 52 of these send continuous signals to Taipei Center where an early warning system is now under development (Teng, *et al.*, 1997). The TSMIP has 612 free-field stations. This figure also shows the main geological divisions and the longitude and latitude scales of Taiwan. Some locality names referred to in the text are also indicated.

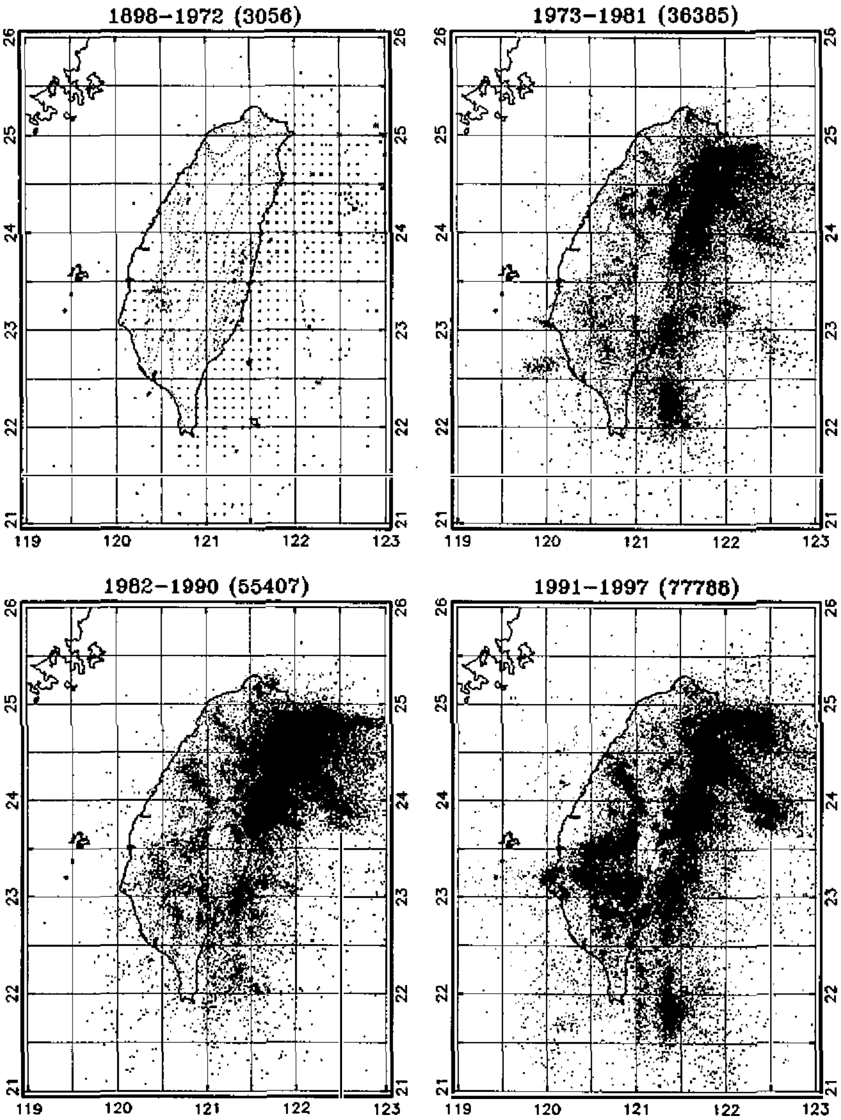


Fig. 2. Different plots correspond to the seismicity recorded at different periods. Only large earthquakes (M>4) are reported in the 1898-1972 period (average: 100 events per year, the first period and the second period). Most of their locations are assigned at 10km x 10km grid positions. Much higher seismicity was recorded during 1973-1981 and 1982-1990 (average: 5,000 events per year, the third TTSN period). The recorded seismicity has multiplied rapidly for the modern CWBSN (1991-1997, average: 12,000 events per year), especially those on the land.

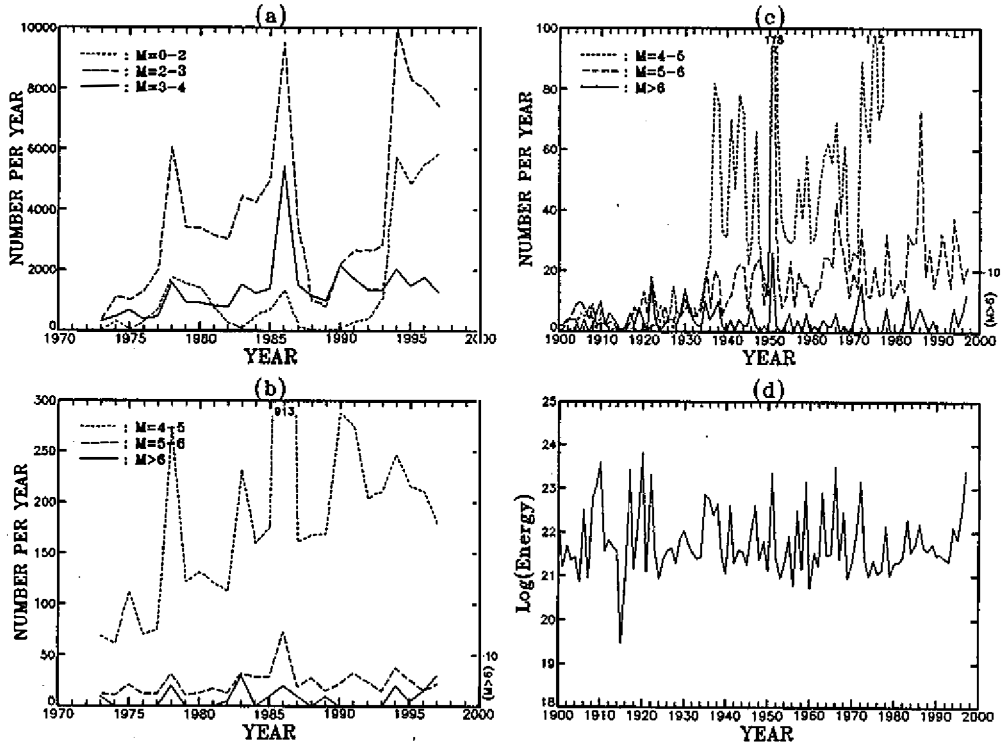


Fig. 3. The temporal seismicity distribution (*i.e.*, number of earthquake per year). (a) and (b) are for the years 1973-1997, and (c) and (d) are for 1900-1997. (d) displays the energy release rate calculated by the Gutenberg-Richter relation. It seems that the variation of annual earthquake number is quite random, and no simple regulation can be found.

detecting ability during different periods, especially those with the magnitude smaller than 5. However, if counting on the records after the TTSN time (Figure 3(a) and (b)), we may have an implication that high seismicity happens every 8 years. In 1978, 1986, and 1994, there have higher seismicity than other years. After 1994, the number of small earthquakes (M<3) increases tremendously which reflects the careful management of the CWBSN operations.

3. TAIWAN SEISMICITY DISTRIBUTION PATTERNS

In the following, we will use a number of figures to illustrate the Taiwan seismicity based on the 100-year data. These figures are plotted in either 2D or 3D, in which the trajectory projection technique is sometimes applied to exhibit their 3D configuration. We will pay special attention to the distribution patterns which could be of particular tectonic significance.

In Figure 4, the two lower plots show the seismicity in 3D with earthquakes projected onto two side planes. These two 3D plots appropriately reveal different seismicity depth distributions in the northern and southern halves of Taiwan. In the northeastern offshore area, the PSP is subducting northward, and in the southeastern offshore area, the SCS plate is subducting eastward. On the land of western Taiwan (top plot of Figure 4), a large amount of seismicity has accumulated around the southern border of the PKH, *i.e.*, in the Chianan area. This seismicity seems to appear as groups of swarms, especially along the 23.2° latitude. In the northwestern Taiwan, two interesting linear seismic patterns appear. The southern one is called the Tunghsiao-Puli linear pattern and the northern one called the Tao-Chu linear pattern. It is apparent that all the seismicity in the different parts of Taiwan is closely related to the surrounding tectonic setting. We will discuss this more in the next section.

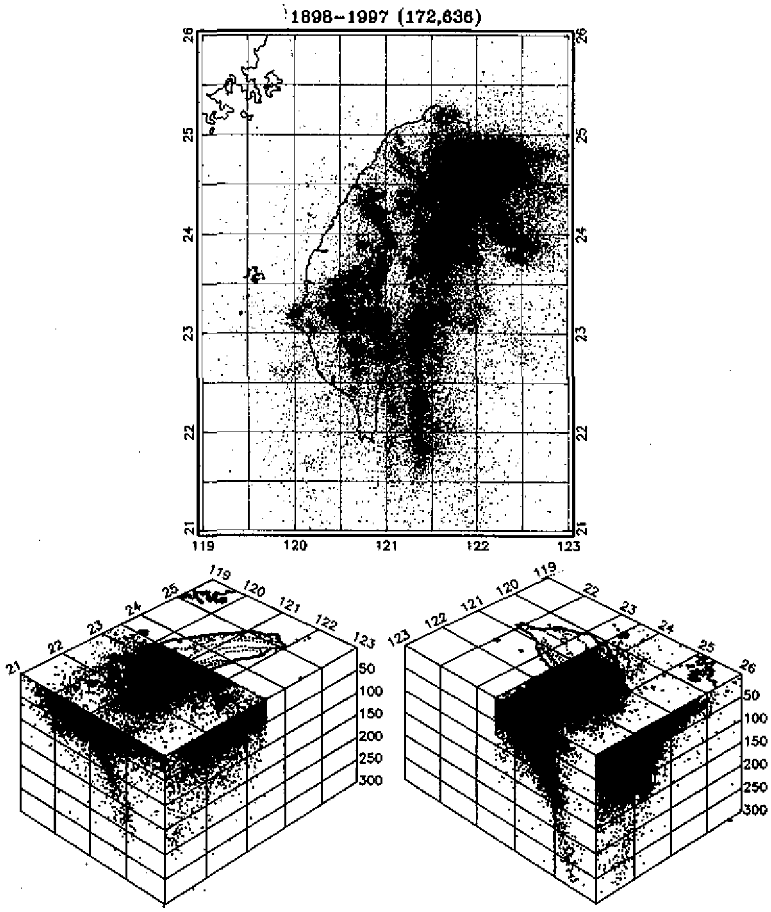


Fig. 4. The seismicity around Taiwan over a 100-year period (1898-1997). 172,636 earthquakes are included. The smallest earthquake has a magnitude of 1.1 and the largest 8.3. The two lower plots show the seismicity in 3D with earthquakes projected onto two sides. This reveals the different subduction systems that exist in the northern and southern halves of Taiwan.

Figure 5 shows a popular cartoon-like picture adopted from Angelier (1986) and its comparison with the seismicity. This figure interestingly describes the tectonic units and their movements in the Taiwan area. Two different tectonic systems are in action: the PSP system in the northeast and the SCS plate system in the southeast. The SCS system existed earlier which gave birth to the Central Mountain Range as its accretionary wedge (Reed *et al.*, 1992). The PSP system is the principal prevailing system at the present, which involves in the current arc-continental collision, moving the Tertiary volcanoclastic Coastal Mountain Range and hitting the Eurasian continental margin. Comparing the two plots in Figure 5, we find that the northward subduction of the PSP offshore of northeastern Taiwan is shifted too far south in the cartoon model. Some of the shallow earthquakes in northeastern Taiwan may not be involved in defining the plate boundary. In addition, the important PKH is not properly indicated in the cartoon plot.

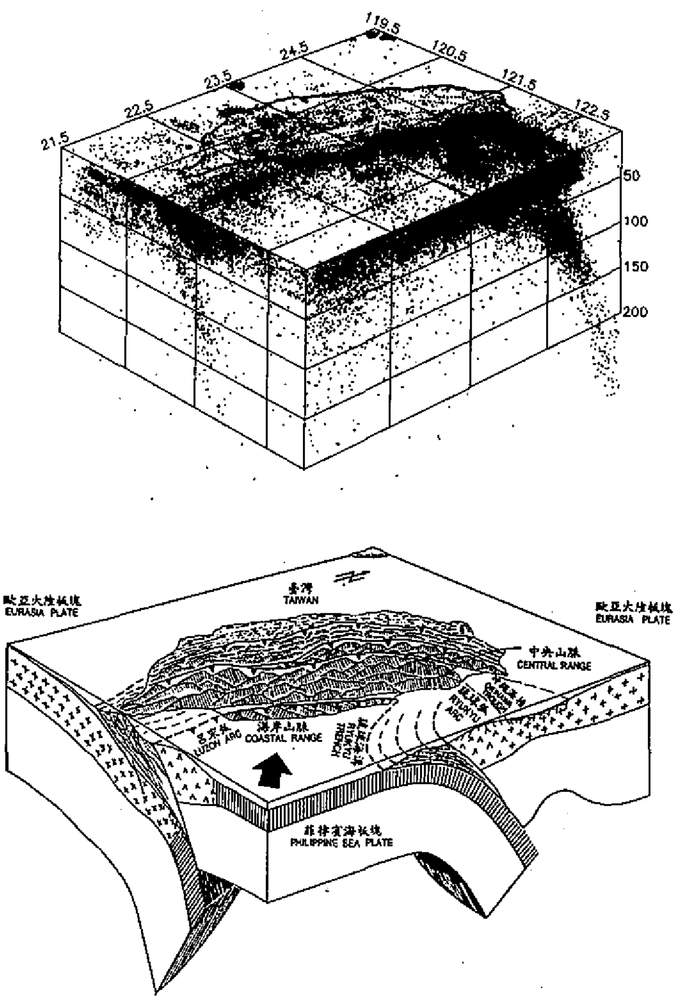


Fig. 5. Taiwan seismicity and its relationship with the tectonic setting around Taiwan. The lower plot is adopted from Angelier (1986), a popular cartoon which interestingly describes the important tectonic movement in Taiwan. Only the earthquakes south of the latitude 23.5° have been projected on the southern profile. The northward subduction of the PSP offshore northeastern Taiwan is a little too far south and the SCS offshore southern Taiwan a little too far east in the cartoon model.

Figure 6 shows Taiwan earthquake distributions at different depth ranges. Most of the earthquakes are shallow, which can be seen in the first two plots of Figure 6. In fact, about 70% of the reported earthquakes are shallower than 20 km. These shallow earthquakes have almost completely defined the areal seismicity distribution. Four apparent groups are found for earthquakes at depths between 20 km and 40 km in the western Taiwan, including those under Hsinchu, Miaoli, Pingtung, and offshore Tainan. The first two groups, which belong to the two linear patterns mentioned in Figure 4, seem to meet at a point near Hualien. At depths greater than 40 km, most of the earthquakes are concentrated in northeastern Taiwan and its offshore area. These earthquakes are related to the PSP system. There is no doubt that the PSP boundary has reached the Tatun volcanic group (north of Taipei basin). Deeper earthquakes spread further more away from the island. In the plots with depths greater than 60 km, we find that the seismicity is aligned along a line at a 10° angle off exact east. This means that the PSP is not subducting exactly toward the north but is shifted slightly eastward. Except at the northeastern corner, not too many earthquakes deeper than 40 km are found on land.

Besides the depth, the magnitude is another important parameter to describe the earthquake. Here the local magnitude M_L is reported. Earthquakes with different magnitudes are displayed in Figure 7. Basically, earthquakes of different magnitudes have similar distribution patterns, which means that large and small earthquakes occupy similar locations. Although the b-value study reveals that the seismicity has a certain relationship with the local geology (Wang, 1988), the plots in Figure 7 imply that it may not be so restricted. However, large earthquakes do seem to gather in the northeastern offshore region, especially near Hualien. Two groups of earthquakes offshore of Hualien have very high seismicity including both small and large earthquakes, one near the location (121.7°, 24.0°) and the other near (122.5°, 24.0°). They seem to be induced by the near-surface thrusting of the PSP subduction. In land, the Chianan area has more large earthquakes than other places. Four big on-land earthquakes are worth noting: 1909 Taipei (M=7.3), 1935 Miaoli (M=7.1), 1906 Meishan (M=7.1), and 1941 Chungpu (M=7.1). The 1935 earthquake is inside the zone of the Tunghsiao-Puli linear pattern in northwestern Taiwan, where actually does not have too many large earthquakes (M>4).

The Taiwan earthquake distribution can be more fully described by using a stereo trajectory projection. Figure 8 shows such a plot. In this figure, with a view angle from below we can see the blooming earthquakes like a waterfall tumbling into the deep earth. The seismicity caused by the plate subduction is very obvious, which has the dimension almost the same as that of Taiwan island. It is interesting to see the distribution of two groups of shallow earthquakes outside Hualien and Ilan (Figure 8(b)). Their relationship with the subducting plate geometry is not so direct. Hualien group is under direct collision of plates and has higher activity, but Ilan group is probably caused by the back-arc expansion. The seismicity in the northeast is very condensed, but in the south it is sparse. Actually, about 60% of the earthquakes with M>3 are clustered in the northeastern offshore area.

4. DIVIDING THE SEISMICITY INTO FOUR SYSTEMS

The interaction of the three tectonic units, *i.e.*, PSP, SCS, and PKH along their boundaries creates earthquakes throughout Taiwan. We can divide the seismicity into four systems de-

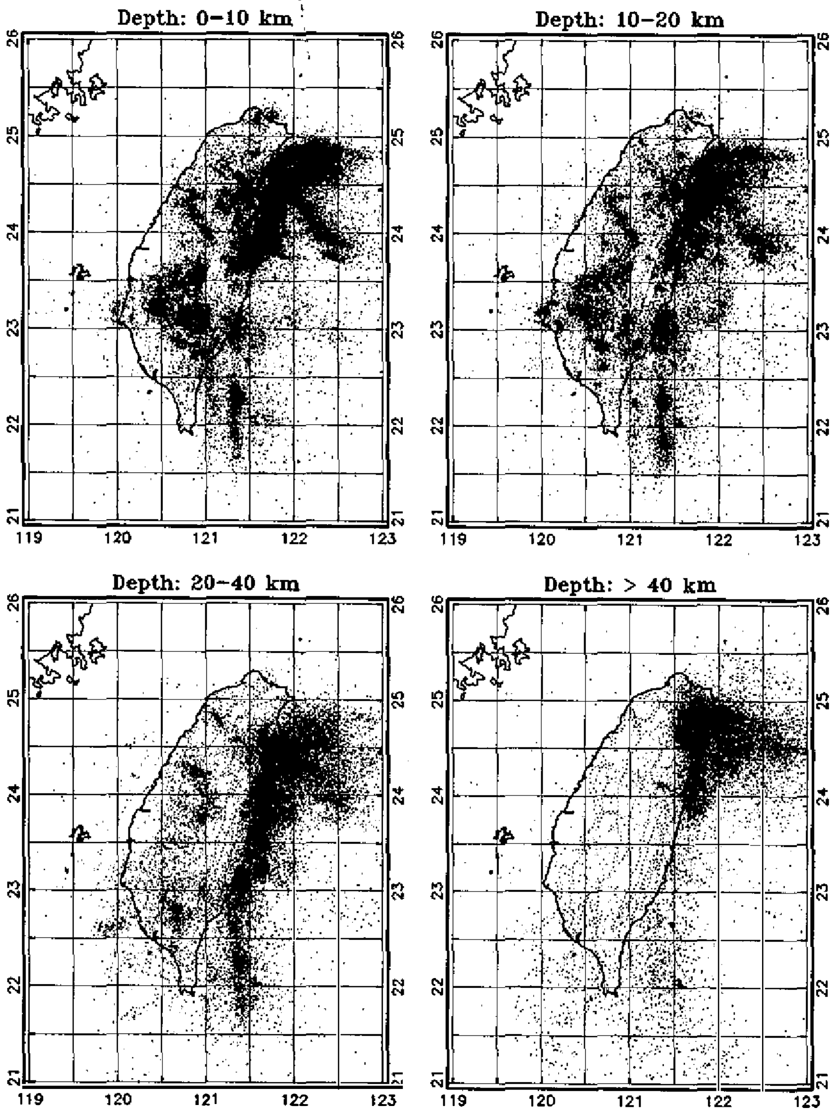
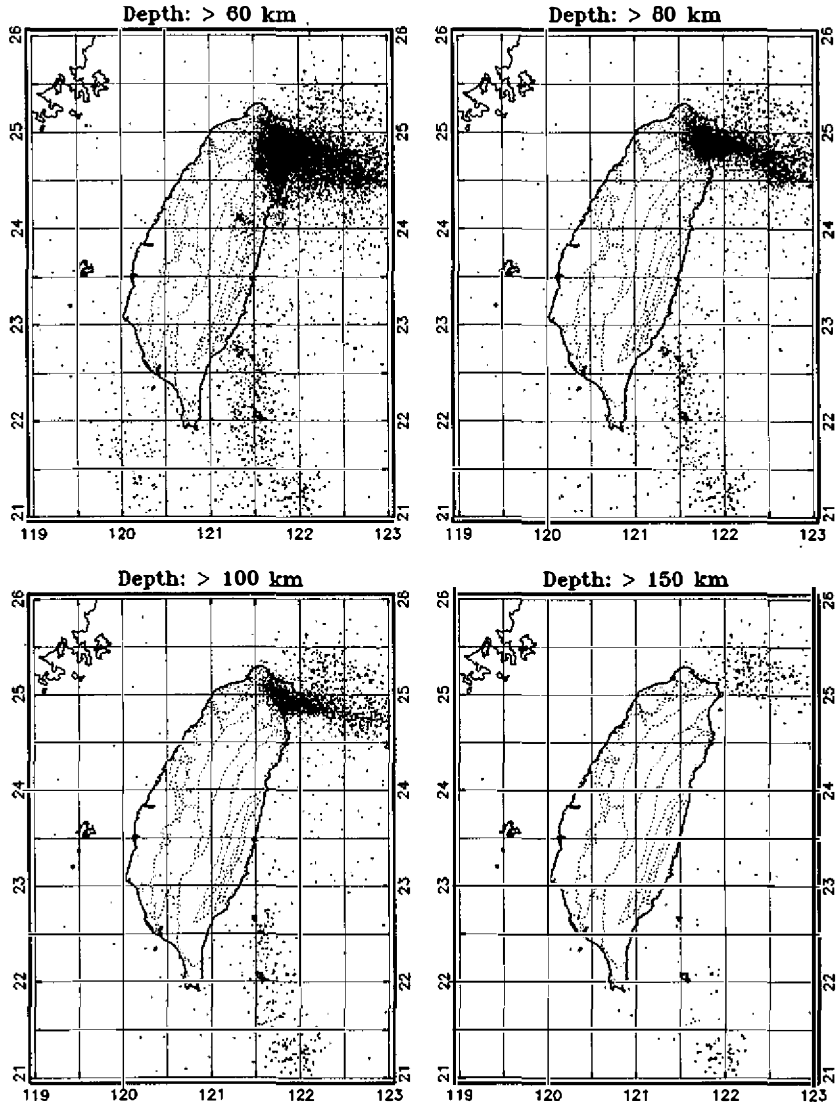


Fig. 6. Depth distribution of Taiwan seismicty. Most earthquakes (about 70%) were shallower than 20 km. The depth gets deeper for earthquakes in northeastern Taiwan, particularly in the offshore area. It is interesting to see that many deep earthquakes occur near the Tatun volcanic group and Taipei basin along the longitude 121.5°. Earthquakes with depths greater than 60 km lined up with 10° angle away from due east. On land, some interesting earthquake concentrations are visible between the 20 and 40 km depth. There were not many earthquakes with depths greater than 40 km on land.



(*Fig. 6.* continued)

pending on their geographic positions and seismicity patterns: 1) NE: the Ryukyu subduction system, 2) SE: the Philippine Sea Plate boundary system, 3) SW: the South China Sea attached system, 4) NW: the northwest overthrust bending system. These four seismicity systems represent the current status of the plate collision around Taiwan, and the explanation of seismicity can be consequently made based on them.

A detailed examination of the three seismicity systems, the NE, SE, and SW, is illustrated in Figure 9. The displays in the left-hand column of Figure 9 are projections of earthquakes (M>3) onto two side planes for the three different systems. The depth profiles on the right project the selected earthquakes onto a vertical plane to show the subduction angles. The

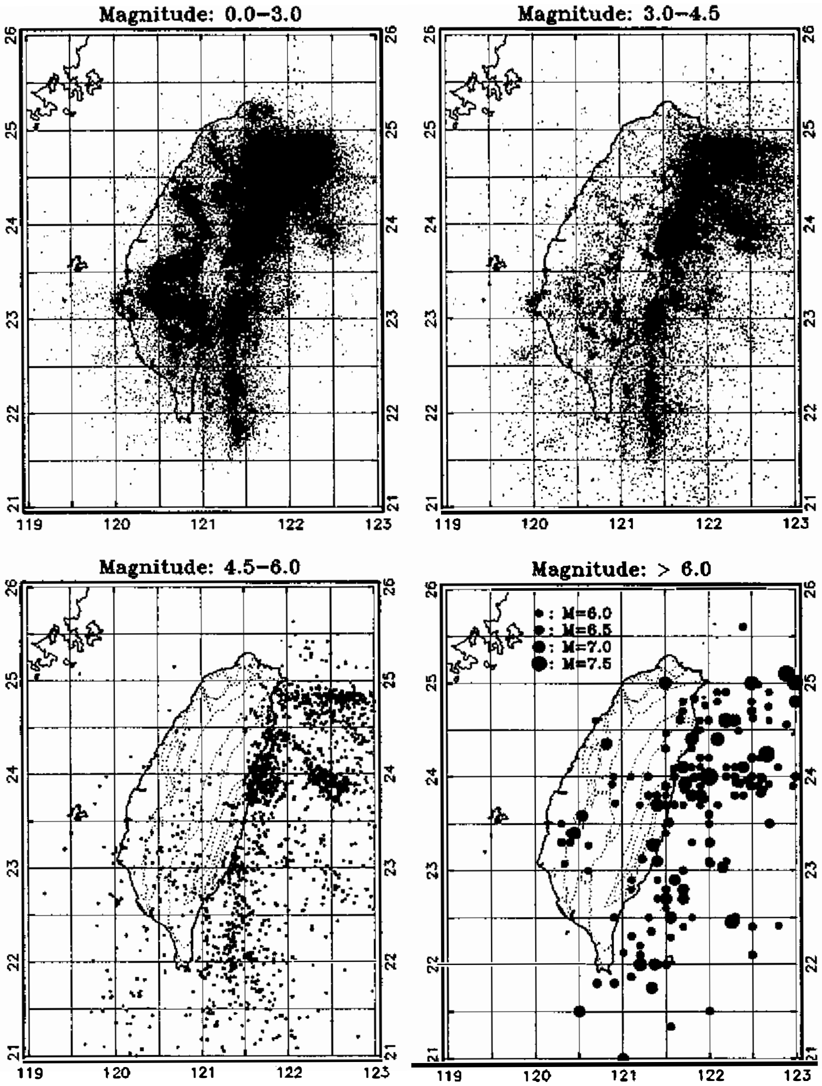


Fig. 7. Magnitude distribution of Taiwan seismicity. The seismicity distribution patterns are similar for different magnitude ranges. However, big earthquakes were gathered offshore Hualien. The Chianan area does have more large earthquakes than other places on the land.

horizontal and vertical axes have the same scale in these depth profiles. In the NE (Figure 9(a)) and the SW (9(c)), the vertical plane on which the earthquakes are projected has been rotated clockwise by 10° azimuth angle. This means the direction of plate movement is not exactly toward the north, but shifted to 10° NE. On the contrary, the SE system (Figure 9(b)) does not have any angle shift, since the SCS plate subducts exactly to the east.

It is interesting that all these three systems suggest planar dipping sesimicity patterns, although their dipping angles may be different. In the NE system, an apparent bend of the dipping plate, from an angle of 57° to 72°, occurs at a depth of 120 km. A distinct drop of earthquake number exists across this depth. The earthquakes offshore of the Ilan plain (*i.e.*, along 24.7° latitude) rest just above the 100 km plate subduction depth. In fact, this group of earthquakes are located in the extension direction of Okinawa trough (Figure 5), hence they are caused by subduction friction effect and not on the subducted plate itself. The PSP starts to subduct at a latitude of 24.0° near Hualien, so many large earthquakes accumulate at this latitude. A gap exists around the latitude 24.3°, which seems to separate the north Ilan group and the south Hualien group.

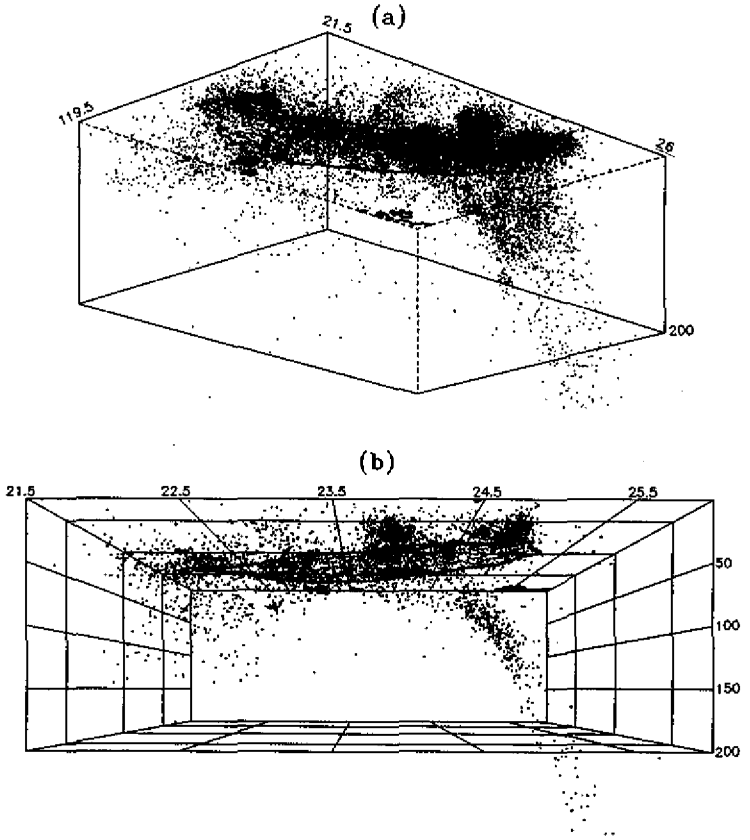


Fig. 8. Two stereo trajectory projections of Taiwan earthquakes. To clarify, only earthquakes with magnitudes greater than 3.0 (a) and 4.0 (b) are plotted. The viewing angle is from below. The seismicity caused by the plate subduction is quite obvious having dimensions almost the same as that of Taiwan island.

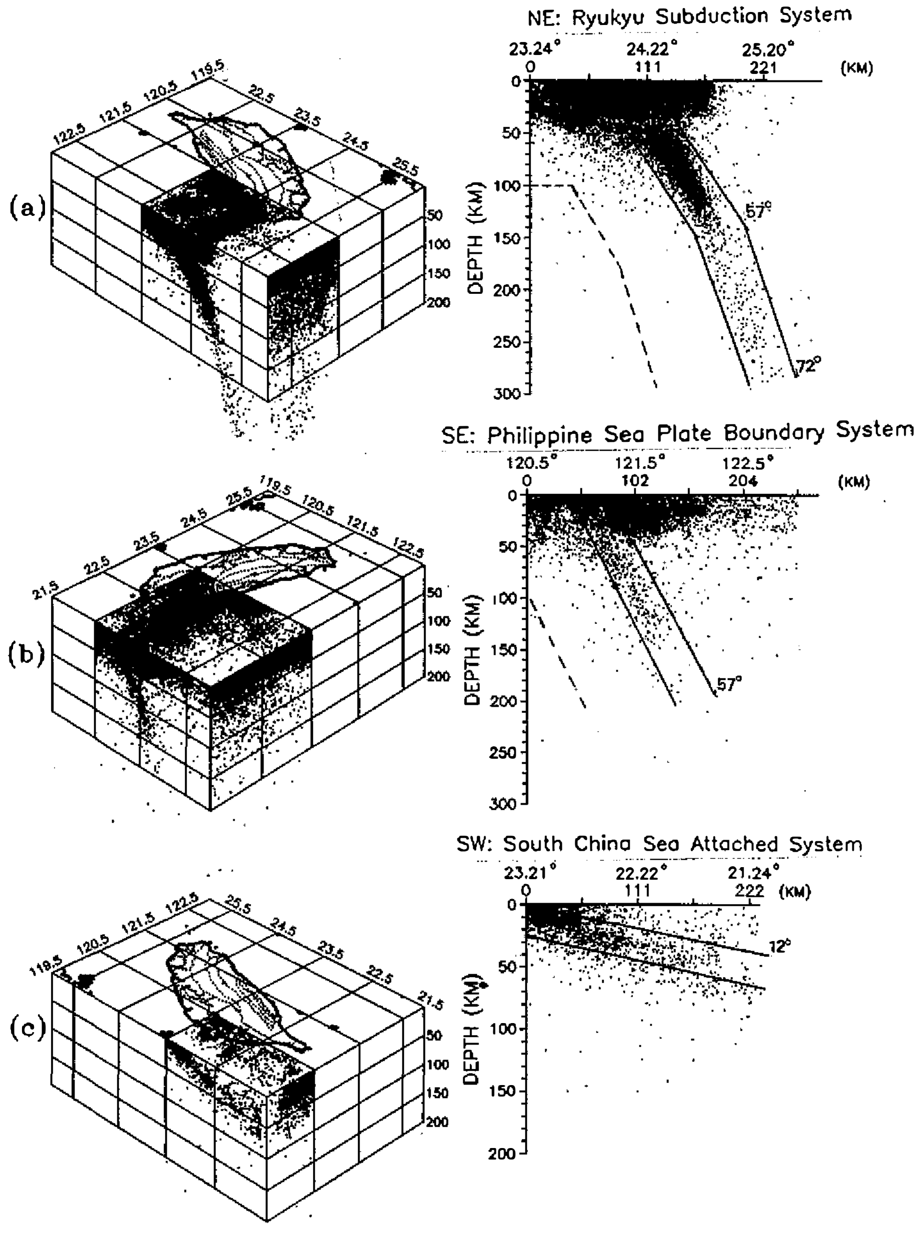


Fig. 9. Three plate boundary interaction systems. The depth profiles on the right show the subduction angles. The horizontal and vertical axes have the same scale. In the NE (a) and the SW (c), the vertical plane on which the earthquakes are projected has been rotated by a 10° azimuth angle. The SW system is actually not a subduction system, but is the interaction of the SCS plate (attaching to the continental margin) against the PKH.

In the SE system, the SCS plate has a dipping angle of 57° moving directly east. There are two nearly north-south linear seismicity trends on the earthquake map (top frame of Figure 4), one along the 121° longitude and the other along 121.3°. Figure 9(b) shows that the SCS plate starts to subduct along the 121° longitude, *i.e.*, passing the southern tip of the Longitudinal Valley. Two small volcanic islands (Lan-Hsu and Lu-Dao, along the 121.5° longitude; Figure 1) outside Taitung, are located just above the 100 km depth of the subduction plate. The linear seismicity along the 121.3° longitude passes through the southern tip of the Coastal Mountain Range. In fact, the depth distribution of the seismicity on this cross section (Figure 9(b)) has an apparent jump from 40 km to 20 km across this longitude. Hence, we suggest that the 121.3° longitude is a boundary of the Philippine Sea Plate, and west of it belongs to the South China Sea plate system. The SCS seismic concentration zone has its western border extend to the 120.6° longitude along the Chaochou fault. The Chaochou fault also runs north-south and its seismicity is nearly vertical with depths extended to 40 km. This is an evidence that the Hengchung Peninsula is under compression due to the mutual interacting force of PSP and SCS and being blocked at the western border of Central Mountain Range where forms the Chaochou fault.

A planar seismicity distribution, though less apparent, is also found in the SW system (Figure 9(c)). It is quite curious that this has not been emphasized in the documentation before. This planar distribution can even be seen more clearly in the longitudinal slice plots in Figure 13. After carefully examining its 3D projection, we find that this planar earthquake zone has an azimuth slightly shifted 10° to the east, slightly tilted to the west by 10°, and with a southward dipping angle of 12° as shown in Figure 9(c). This seismicity surface inclination may indicate that the South China Sea plate being hindered by the passive continental margin. It seems that the SCS system is attached to the Eurasian continent. This seismicity zone meets the ground surface between 23.0° (Tainan) and 23.5° (Chiayi) latitudes. The inclination is believed to be greatly influenced by the PKH which might extend to the bottom of Yushan (the highest mountain on Taiwan island, located at (121°, 23.5°)). After careful measurement, we find that an uplifting center can be set under Yushan. With this observation, we propose a model that the 10° azimuth shift away the north might be related to the opening of Pingtung plain in southwestern Taiwan. This is a tilted and twisted plate boundary which spreads earthquakes throughout southwestern Taiwan. This southwestern slant plate boundary develops until it crosses over the Chaochou fault, and after that the plate starts to subduct toward the east. This is an interesting model but it needs more work for better delineation.

Figure 10 presents 3D stereo plots of the seismicity for the four systems, *i.e.*, NE, SE, SW, and NW, from a viewpoint below the surface. The different seismic zones involved in the first three regions have been explained in Figure 9. The seismicity lineup is even more obvious in this figure. The fourth region exposes an area the same as that in Figure 12(a), *i.e.*, the Tunghsiao-Puli linear pattern, which will be discussed later. In Figure 10, apparent planar seismicity distribution patterns are easy to recognize. This is a strong evidence that the Taiwan earthquakes are mostly caused by a number of active seismic zones.

The seismicity pattern in western Taiwan is more complicated than that on the eastern offshore area. We may isolate some different zones for discussion. Figures 11 and 12 show such a display. Figure 11 shows three seismic zones in southwestern Taiwan. The earthquakes

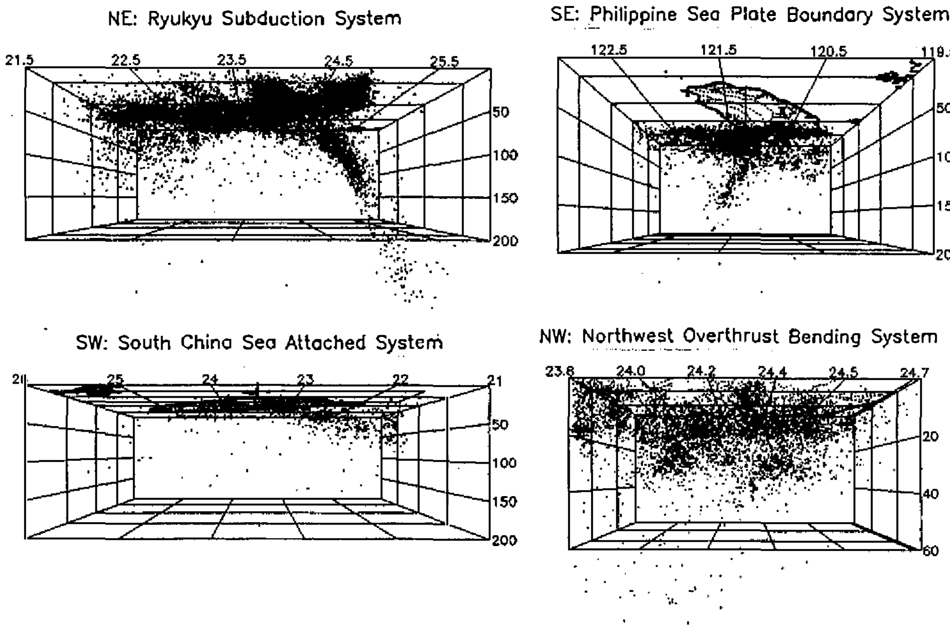


Fig. 10. 3D stereo plots of four Taiwan earthquake systems. The viewer is from below. The seismicity lineup is quite obvious. The fourth (NW) region exposes an area (similar to that in Figure 12(a)) gives the Tunghsiao-Puli linear pattern. Apparent linear seismicity distribution patterns are easy to see in all four plots.

are very shallow (< 20 km) in the seismic zone along the immediate southern border of PKH (Figure 11(a)). This seismic zone seems to follow a big discontinuity in the PKH, *i.e.*, the Yichu fault (Tang, 1977; Hsu and Sibuet, 1995), extending into the continental margin where the Tainan basin is located (Yang, *et al.*, 1991). These earthquakes are spread over an area northwest of the deformation front (Lee *et al.*, 1993; Liu, *et al.*, 1997), or the Manila trench, which is believed to land on the southwestern coast near Tainan after taking a big curve offshore of Kaohsiung. This means that the shallow crust in the 'front' of deformation front is pushed to climb up the PKH, which produces the earthquakes. In the east this seismic zone may reach as far as Yushan.

For the seismic zone along the 23.2° latitude (Figure 11(b)), earthquakes are concentrated along a subsurface belt, with a cross section of about 20km X 20km. This belt is not oriented exactly east-west, but shifted a little to the SE by an angle of 10° (the same as we have seen in Figure 9(c)). Its seismicity emerges as groups of swarms which are mostly composed of many aftershocks following a main earthquake. This implies that the rock material is brittle and easily fractured. Figure 11(c) shows the seismicity lineup along the Chaochou fault (following the 120.6° longitude). This boundary is nearly vertical and deep (40 km). A close examination of the seismicity in the southwestern Taiwan region (*e.g.* Figure 13) indicates that there is a 0.3° gap which lacks earthquakes around 22.6° latitude. This gap passes through Kaohsiung

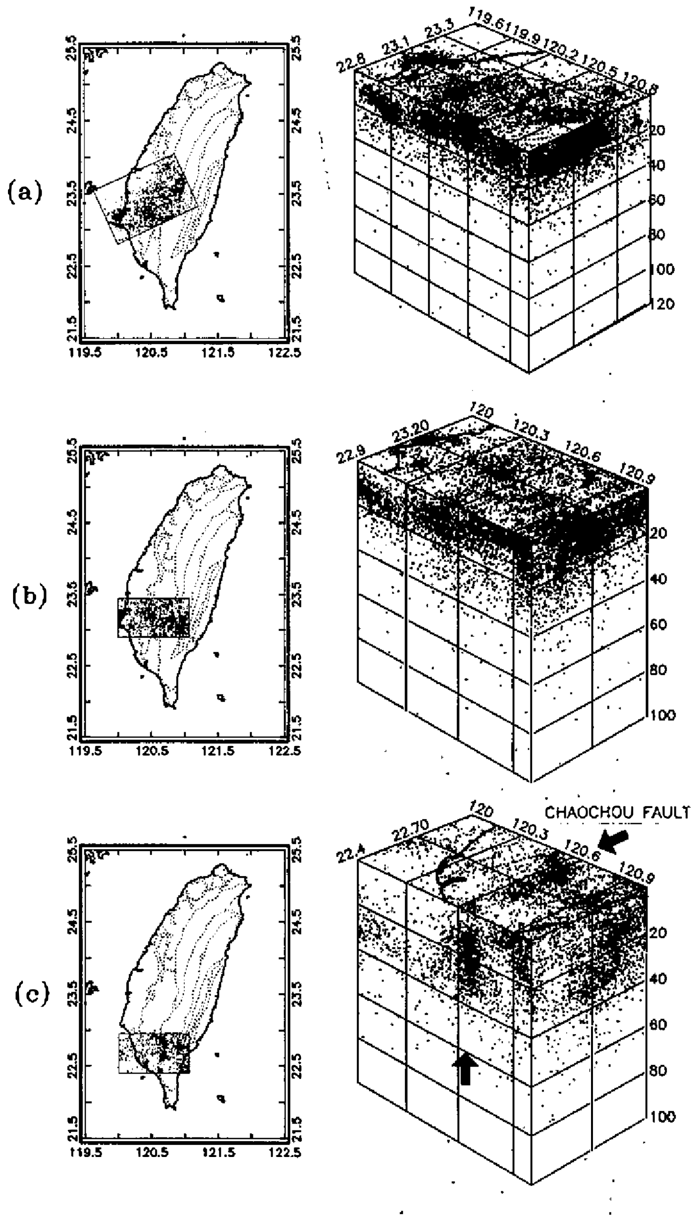


Fig. 11. Three SW seismic zones. The earthquakes are very shallow (< 20 km) in the seismic zone immediately south of the PKH (a). For the seismic zone along the 23.2° latitude (b), the earthquakes are concentrated in a shallow belt having a cross section of about 20km X 20km. (c) shows the lineup of Chaochou fault, along the longitude 120.6°. This boundary is nearly vertical and reaches a depth of 40 km.

and the central Pingtung plain where a Bouguer gravity low has been found (Yen *et al.*, 1996). This may be explained by the afore mentioned 10° rotation of the SCS plate in southwestern Taiwan. The rotation might open the Pingtung plain creating a weak zone which is easily deformed and is not stiff enough to generate earthquakes (Yu and Chen, 1994).

Figure 12 displays the two seismic zones in northwestern Taiwan. Figure 12(a) and (b) are for the Tunghsiao-Puli linear seismic zone, and (c) is for the Tao-Chu linear seismic zone. Compared to Figure 11, we see that earthquakes in northwestern Taiwan have a larger depth distribution (down to 80 km). On the vertical profile, it is interesting to see an aseismic gap at about a depth of 18 km, suspected to be a 'decollement' surface as in Suppe's thin-skinned model (Suppe, 1984). However, below 20 km some deep earthquakes also appear (Rau and Wu, 1995) and especially some of them line up, as indicated by the arrows in Figure 12. The 1935 earthquake, denoted by a white point Figure 12(a), is located just at the place where this deep linear zone comes up to meet the surface. When discussing the seismicity depth distribution in Figure 6, we have found that a deep linear seismicity starts from a point under Hualien and develops into two linear seismic zones in northwestern Taiwan. Figure 12(b) shows the linear pattern that earthquakes with depths greater than 20 km may follow. In addition, Figure 12(c) shows the seismicity distribution of the Tao-Chu linear seismic zone which also involves deep earthquakes. It is known that a Kuan-Yin High (KYH) exists in the NNW offshore of Taiwan (Figure 1). The two basement rises, *i.e.*, the PKH in the south and the KYH in the north, may represent two standing blocks stopping the movement of the northern Taiwan mountain belt and leading the Miaoli foothills to bend and intrude in between. From the seismicity revealed in this paper, we courageously propose that a tectonic point force strikes at Hualien (Biq, 1981) producing two fracture lines, one toward the PKH and the other toward the KYH. In the south, a horizontal decollement surface makes this linear fracture pattern detach and rotate by an angle until following the PKH's boundary. In the north, it simply climbs up the KYH. Teng and Lee (1996) proposed a boundary between the extensional and the compressional regimes in northern Taiwan. This boundary sits just along the Tao-Chu linear pattern. The seismicity does seem to support the existence of such a boundary.

The above discussion should have drawn a gross picture of Taiwan seismicity within the framework of tectonic interaction. To seek better confirmation to this picture, we can further slice the seismicity, as those shown in Figures 13 and 14. Figure 13 shows the seismicity as north-south slices and Figure 14 as east-west slices. Each slice has a width of 0.2° and is displayed from west to east and from north to south, respectively. These sequential slices can be scanned like a series of snapshots. In Figure 13, it is apparent that southward dipping seismicity emerges before the longitude of 120.8°, as discussed in Figure 9(c). A transition from the south SCS system to the north PSP system happens between the longitudes 120.8° and 121.4° where the old Central Mountain metamorphic rock material is situated. After the 121.4° longitude, the northward subduction zone of PSP becomes more and more apparent at the locations north of the 23.5° latitude. We even can see three seismicity gathers in this subduction zone between the longitudes 122.2° and 123.0°. The first is near Hualien (latitude 24.0°) where the plate starts to incline, the second is near Ilan (latitude 24.7°) where it is above the 100 km depth of the subduction plate, and the third is near the 120 km depth where the plate is bending. The seismicity becomes disperse below the 120 km depth.

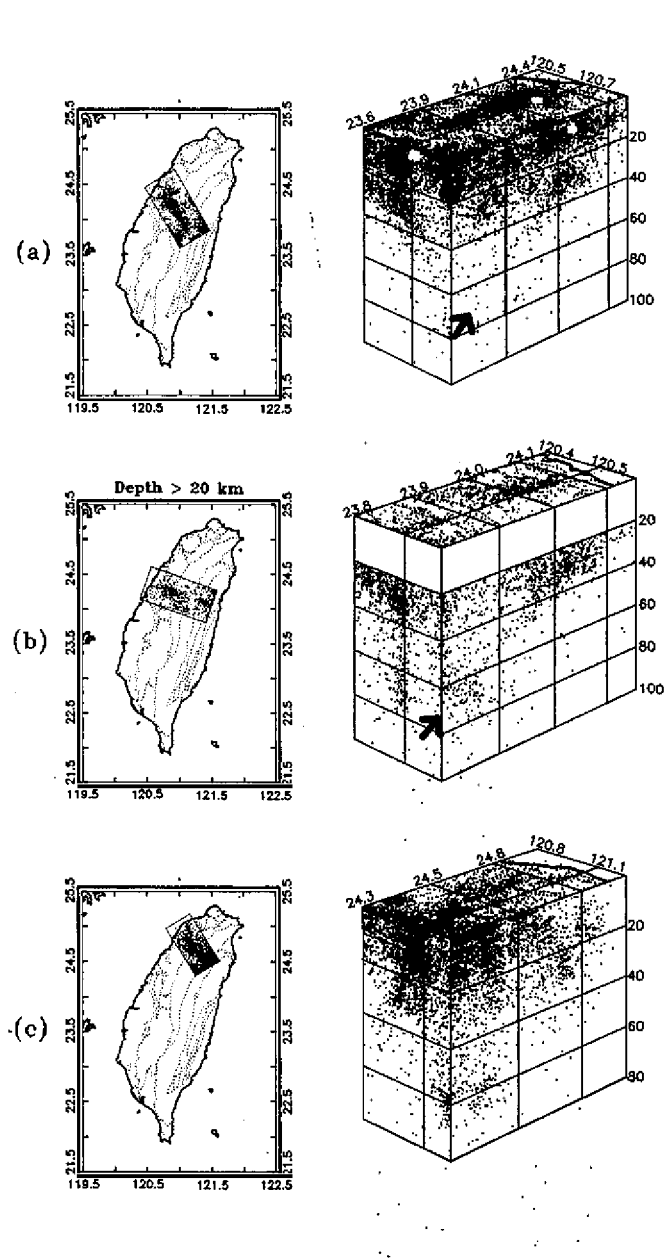


Fig. 12. Two NW seismic zones. Compared with Figure 11, the earthquakes in the NW have a larger depth distribution, however, an aseismic gap seems to exist at the 18 km depth. (a) and (b) show the Tunghsiao-Puli linear seismicity zone, while (b) only shows the earthquakes with depths greater than 20 km, they seem to follow another linear pattern as indicated by the arrow. The 1935 (M=7.0) earthquake is denoted by a white dot in (a). (c) shows the seismicity distribution of the Tao-Chu linear pattern.

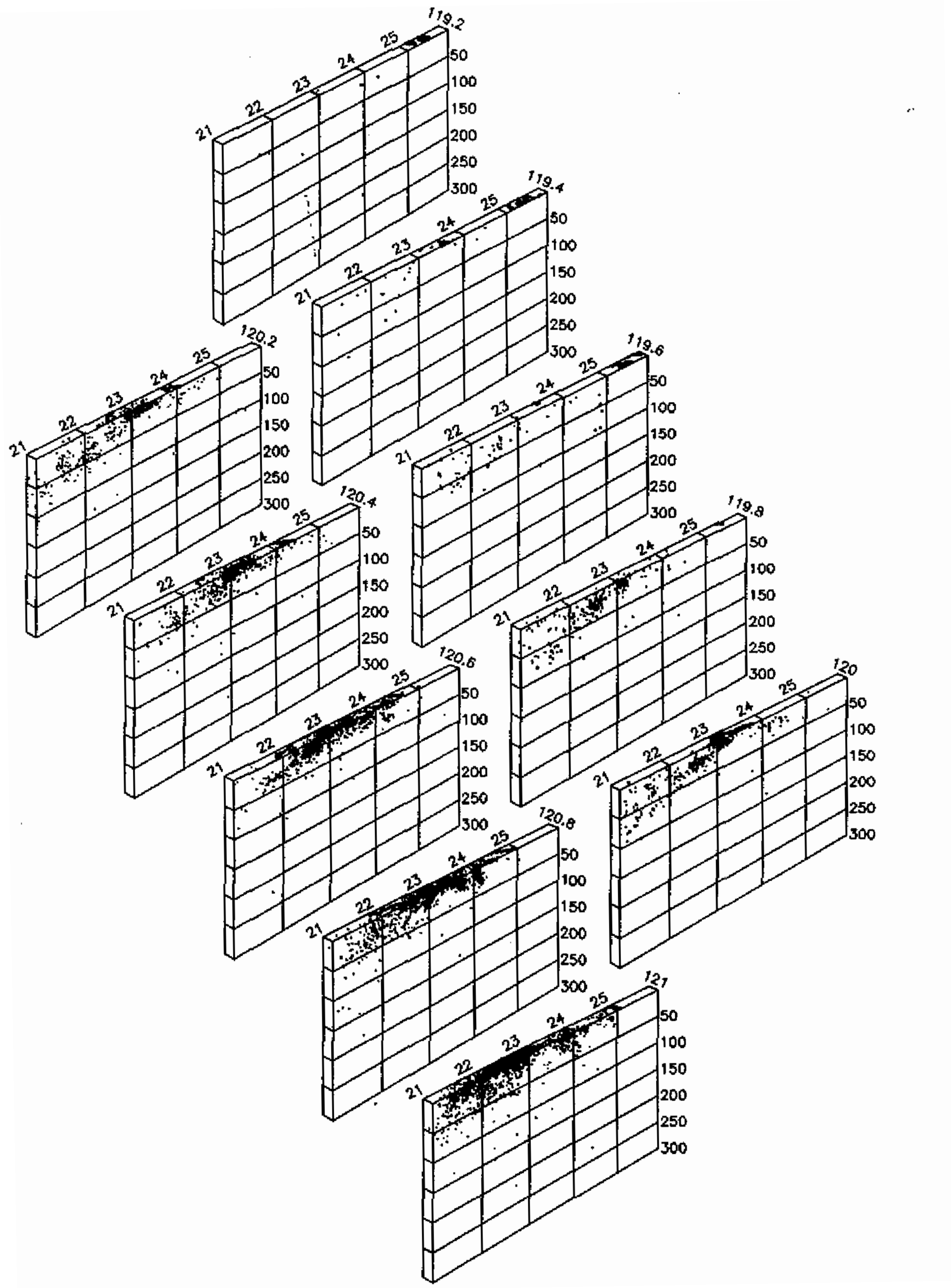
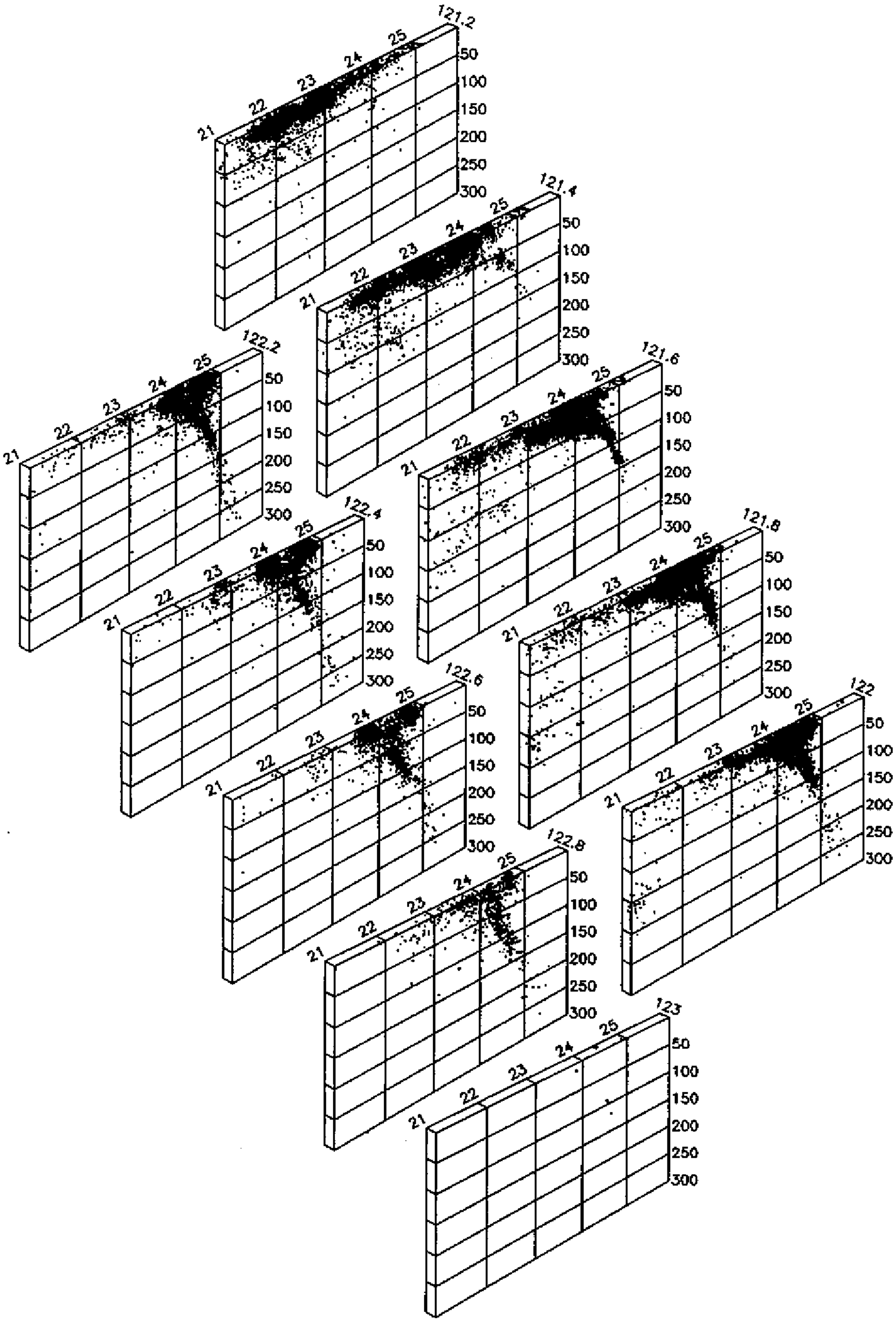


Fig. 13. South-north slices of Taiwan seismicity. Each slice has a width of 0.2° longitude and is displayed from a longitude of 119.2° (west) to 123.0°.



(*Fig. 13.* continued)

Some interesting features can also be seen in the east-west slices (Figure 14). Between the latitudes of 25.0° and 24.4°, the deep seismicity seems to be slightly slanted to the east. This is due to the subduction direction being along the azimuth of 10°-15°, not because of the plate's tilt. An anvil shaped near surface seismicity is found located approximately along a longitude of 121.5° and between latitudes of 24.4° and 22.8°. We wonder whether this might be an indication that the Central Mountain material might have been inserted under the Coastal Moun-

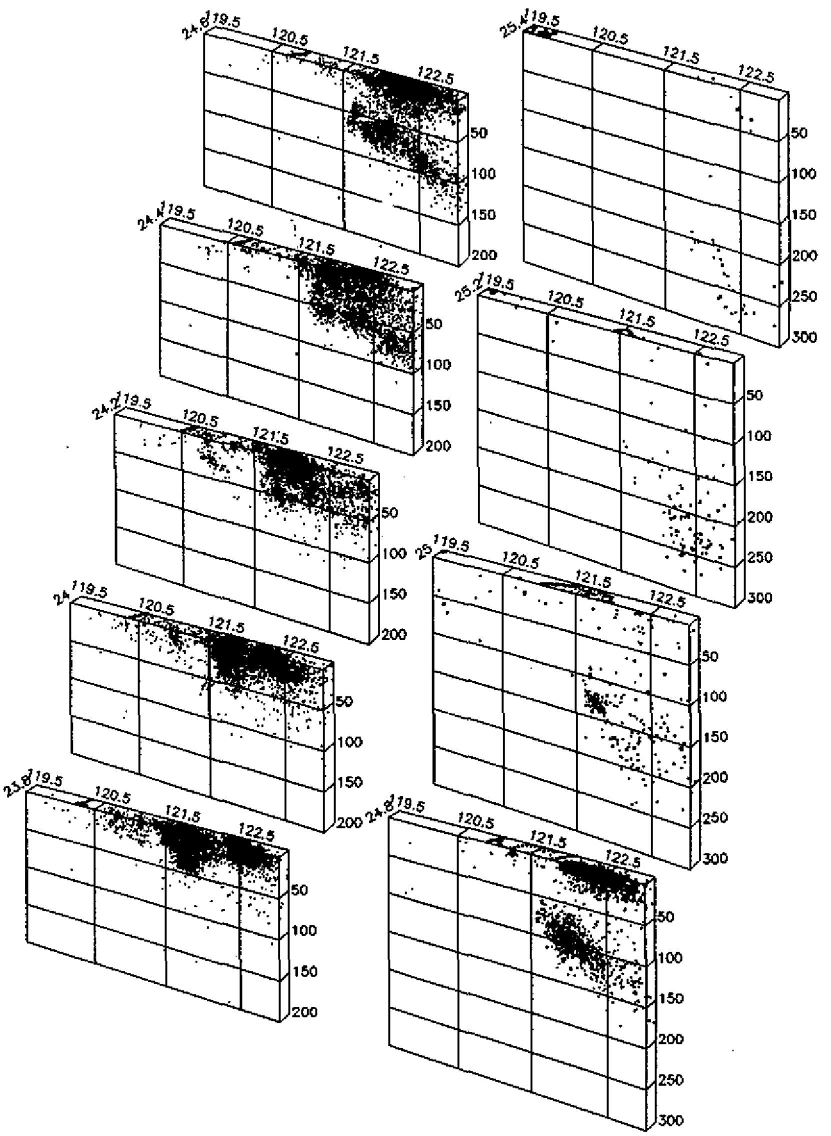
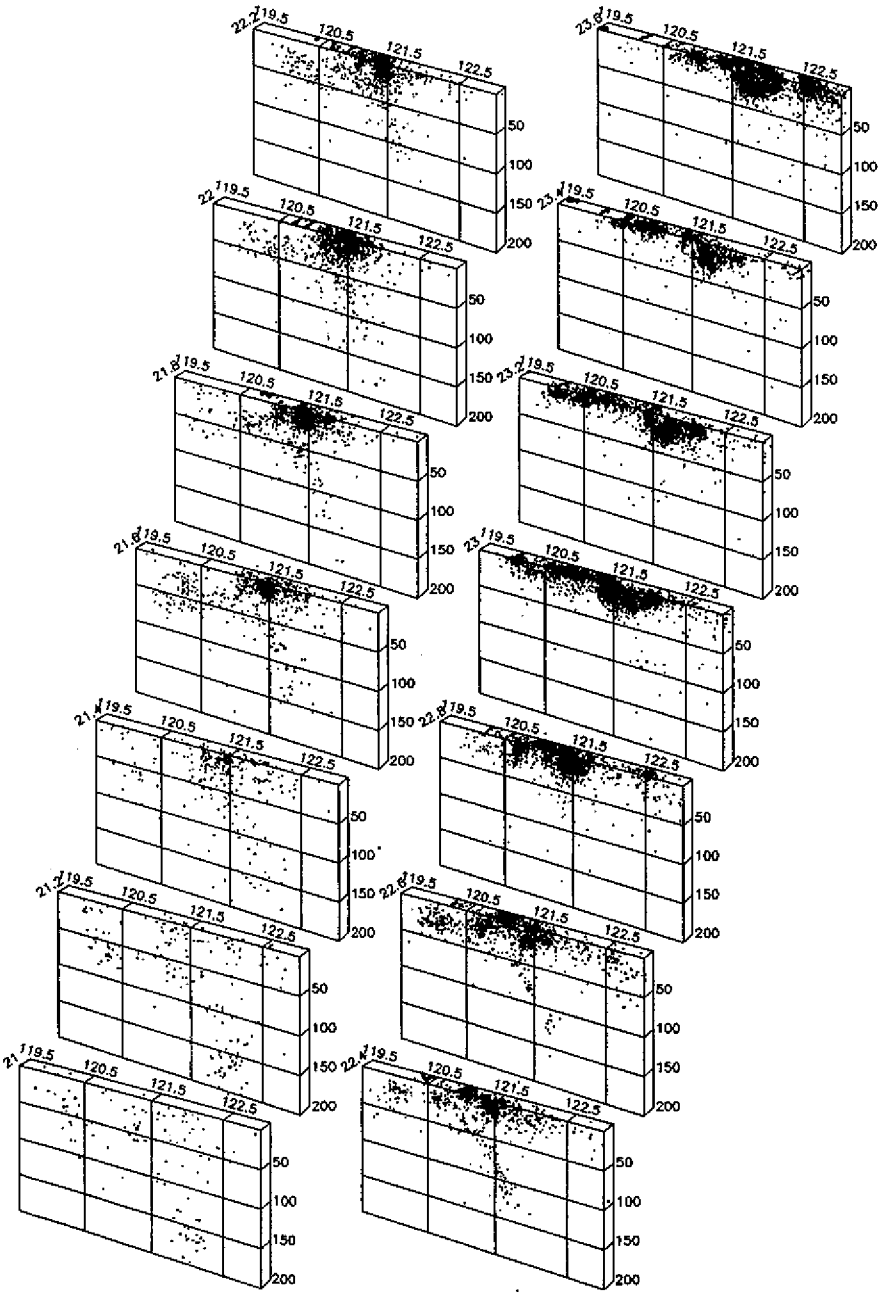


Fig. 14. East-west slices of Taiwan seismicity. Each slice has a width of 0.2° latitude and is displayed from a latitude of 25.6° (north) to 21.0° (south).



(*Fig. 14.* continued)

tain Range, *i.e.*, the latter sits on the top of the former. East of the 120.0° longitude and south of the 23.0° latitude, we can see some eastward subduction of the SCS plate. Earthquakes are sparse there, but denser and deeper earthquakes develop more often toward the south. Many more details can be discovered, if a closer look is taken.

5. CONCLUSIONS

By using 100 years of seismicity records, we depict the earthquake distribution in Taiwan area in both 2D and 3D views. There are about 170,000 earthquakes in this data volume. These earthquake activities can be divided into 4 zones: 1) NE: the Ryukyu subduction system, 2) SE: the Philippine Sea plate boundary system, 3) SW: the South China Sea attached system, 4) NW: the northwest overthrust bending system. All 4 systems are due to the arc-continental collision between the Eurasian plate and the Philippine Sea plate. After extensively examining these seismicity figures, we reach the following conclusions:

1) The Ryukyu subduction system (NE zone): The subduction is directed toward the north but slightly shifts to the east by 10° without any tilt. The subduction plate surface has a dip angle of 57° above 120 km depth and 72° below. The subduction starts at the 24.0° latitude. A linear east-west seismic zone full of shallow earthquakes offshore of Ilan is located just above the 100 km depth of the subducting plate. Earthquakes offshore between the latitudes of 23.8° and 24.2° are also shallow (< 30 km depth), possibly representing the thrusting of the Philippine Sea plate as it bends and subducts. Most of large (M.7) earthquakes occur in this region. The western boundary of the PSP subduction plate may go as far as just below the Taipei basin.
2) The Philippine Sea plate boundary system (SE zone): The Philippine Sea plate moves in, pushing southern Taiwan along a longitude of 121.3, forming an almost south-north linear seismic zone which passes through Taitung. All the earthquakes in this linear zone are shallower than 35 km. This is a direct contact plate boundary, with an anvil-shaped cross section in seismicity. The more stable Central Mountain Range is suspected to have plunged underneath. In this region, it is also apparent that the South China Sea plate subducts toward the east with a dipping angle of 57°. The Hengchung Peninsula is located just at the place where the plate starts to bend and subduct.
3) The South China Sea attached system (SW zone): A seismic boundary surface, dipping 12° southward, climbs from the south and reaches the surface along a latitude of 23.0°, passing through Tainan. This system seems to be stopped by the Pei-Kang High. In southwestern Taiwan this boundary surface is tilted a little to the west and slightly rotated to the east. We wonder whether this twist of plate may open the Pingtung plain causing a weak zone near Kaohsiung and Pingtung where an aseismic gap exists. The SW system seems not to be very active and can be even looked at as attached to southwestern Taiwan, which is now acted on by the Philippine Sea plate movement force.
4) The Northwest overthrust bending system (NW zone): Since this zone is north of the Pei-Kang High, there is no backing unit to stop the plate's movement from the southeast. However, an aseismic depth around 18 km is found, which could be the decollement surface.

The crust of northwestern Taiwan is bent thrusting over this decollement surface. A NW-SE trending Tunghsiao-Puli linear seismic zone is formed where the most damaging earthquake in Taiwan's history happened in 1935. A wedge shaped boundary seems to climb from the southeast (near Hualien) below 20 km, which means a large movement system could occur there from the deep crust or below the crust.

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