Seismotectonics and Identification of Potential Seismic Source Zones in Taiwan

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Abstract

Taiwan is an active and complex tectonic unit. Earthquakes occur as a response to the collision of the Philippine Sea and the Eurasian plates; the northward subduction of the Philippine Sea plate in northern Taiwan and the eastward subduction of the Eurasian plate in southernmost Taiwan. Seismic hazards may either be induced by the plate boundary seismic activities associated with the subduction zones or by the intraplate activities due to plate collision. In the latter category, specially recognized 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 the populated areas. The northern subduction zone is capable of producing $M_W>7.5$ events, but most of the source zone will be offshore. The southern zone is under the Hengchun Peninsula, but the seismicity appears to be relatively low. Also to be noted are long term persistent seismicity patterns. The NW-SE belt from Miaoli to Puli is a zone that extends from near the surface to depths greater than 30 km. It may be a significant zone. The Longitudinal Valley faults and the Meishan fault are well known. The knowledge of such seismogenic structures may help us in taking appropriate long term measures to mitigate seismic hazards.

1 Introduction

Taking into consideration seismic hazards in the long-term planning for further industrial development and land-use can lead to a rational use of resources in the face of risks. Being in a tectonically complex and seismically very active environment, an area-specific identification of seismogenic structures will be more 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 noticed in the recent seismological history; a number of very damaging earthquakes were essentially unexpected and therefore not taken into account in the aseismic 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. The damages to engineered structures resulting from these events demonstrated quite well that were proper design measures incorporated the damages could have been lessened. 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; these faults may be inherently undetectable before the earthquake and are quite hazardous because they often lie under sedimentary basins where population tends to concentrate. 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 and Rau, 1996; see below), the inclusion of blind thrusts in seismic design in Taiwan is a question that certainly needs to be explored in Taiwan.

On the other hand, although the Nojima fault that 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 particular potent. 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 active fault mapping 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), with the exception of the Meishan fault for the 1906 Chiayi earthquake, and the faults activated during the 1935 Hsinchu earthquake. Armed with detailed seismicity in Taiwan and the knowledge that western Taiwan had been very active in the last four hundred years, 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 had been different interpretations concerning the subduction zone under Taiwan (Wu et al, 1996; 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). It is such knowledge that led many to study the seismic risks posed by the Cascadia subduction zone in northwest United States (Kanamori and Heaton, 1996). The subduction zones under Taiwan are, however, near the ends of the zone; will they pose similar hazards? We shall investigate the potential hazards of these zones in light of recent seismicity and GPS data.

With the improved digital data now provided routinely by CWBSN, as well as geophysical data such as GPS, gravity, crustal imaging, etc., it becomes possible to study and understand the tectonics of Taiwan in more detail than 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 tectonics. In this study we use our understanding of tectonics as a basis for deciphering the seismogenic potential of different tectonic units of Taiwan.

2 Tectonic Framework of Taiwan

Taiwan is in a fairly complex tectonic environment with a collision zone lying between two subduction zones as described above and depicted in Figs. 1 and 2. In Fig. 1, the overall plate tectonic environment is illustrated, and in Fig. 2, the interpreted plate tectonic model is superposed on seismicity. Although the Ryukyu Trench ceased to be a depressed bethymetic trench west of Longitude 123°E, the subduction zone complex, including the Yaeyama ridge north of the Trench, continues westward toward Taiwan (Wu et al., 1996). The shallow portion of the western edge of the Ryukyu zone actually underplates the eastern margin of Taiwan north of Hualien for about 20 km. The deeper part of this zone extends further inland and it disappears around longitude 121.5°E.

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 of a line connecting Kaoshiung and Taitung. 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. Onshore the mapping of geology is made difficult by the lack of outcrops, but the major N-S striking Chowchou fault appears to be a thrust.

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. Within this section the mountain building is most active. Many magnitude 7 or above earthquakes occurred under the Coastal Range (or just offshore of eastern Taiwan) and also many damaging earthquakes occurred in historical time under the Western Foothills and the western Coastal Plain (Fang, 1968). A particular feature of the seismicity in western Taiwan is that seismicity is found throughout the top 40 km of the crust. In California and many other continental areas, the seismicity is mostly concentrated in the top 15 km. Within the Taiwan crust, we can discern a double-layer structure of seismicity that is evidently related to the rheology of the continental crust (Wu et al., 1996). 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 it is rapidly rising, implying that the region is deforming in a ductile manner, unaccompanied by seismic events.

3 Potential blind thrusts in Taiwan

Although the Tainan-Chiayi area has a well-documented history of seismicity, partly because that was the center of population since late 1600's, besides the association of the 1906 and the 1792 earthquakes with right-lateral/normal faulting in the Meishan region, the seismogenic structures of other events are not known. For the 1941 Chiayi earthquake, no surface faulting was observed, and based on limited first motion data (Taiwan Weather Bureau, 1942), the causative faulting could also be 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 (Wu et al., 1996). 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.

Judging from the fact that double seismicity layer exists in western Taiwan (Wu et al., 1996), and that Taiwan is under east-west compression, blind thrusts can be expected to occur in much of western Taiwan. Blind thrusts present major problem for seismic hazard mapping, because its presence cannot be detected using surface mapping or even 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 the industrial seismic imaging, which can resolve subsurface structures down to depth of 10 km, will 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) for the area directly above the source. Such high acceleration usually exceeds the design criteria. For critical structures however, sufficient safeguard for such events should be considered.

4 The NW-SE seismic zone in Central Western Taiwan

One of the most persistent trend of seismicity on land is the NW-trending zone stretching from Miaoli to Taichung. It was visible in the TTSN seismicity maps (Tsai et al., 1980), but it became even clearer since 1991 (Figs. 3a and b). It forms a nearly continuous 70 km long vertical zone with magnitude less than 5 events. It extends from shallow depth all the way down to about 40 km, with an interesting break around 20 km. It is one of the few well-identified continental zone that extend to such depth. The focal mechanisms shown in Figs. 3 were determined using P first motions, SH/P amplitudes and the tomographically located hypocenters (see Rau et al., 1996 for more detailed methodology). Of the 25 mechanisms shown in Fig. 3a, seven of them show strike-slip mechanisms, and five of them 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 a 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 even a major strike-slip fault such as the San Andreas fault of California (e.g., Jones, 1988). From the landforms around 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. There are geomorphic features in side-looking radar image of Taiwan that may be related to this fault. There are also several historical events along the trend. No particular evidence can be relied on for estimation of recurrence period.

The length of the fault, if activated at one time, can 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 leading to heavy damage in the Kobe area. For the NW zone, an unilateral propagation toward the southeast, in the direction of the Central Range will 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. There is another belt of concentrated seismicity on the southern side. That zone includes the 1906 Chiayi event. These bounding faults may be important seismogenic structure as the Peikang basement high seems to be a aseismic zone, therefore relatively undeformed compared to its surrounding areas.

5 Subduction zones

As shown in Fig. 2 the northern and southern subductions zones are rather clearly defined by the inclined seismic zones. Both the subduction zones under Taiwan are termini of subduction zones: the northern zone being the terminus of the Ryukyu zone and the southern that of the Northern Luzon-Taiwan zone. With the Philippine Sea plate moving relatively to the Asian plate at about 7 cm/yr in the N55°W (Seno, 1977) direction and the strike of the northern Taiwan zone at about N70°W, the northern Taiwan zone has a down-dip subduction velocity of only ~2 cm/yr; the subduction zone as a whole 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. This could be accomplished if there is enough northward extrusion of the Philippine Sea plate as a result of intraplate deformation (Wu, 1978). The westward motion of the Philippine Sea plate produces the driving force for the collision. Although the bathymetric Ryukyu Trench that is prominent along the length of the Ryukyu arc disappears near 123^{O}E longitude, the E-W trending Yaeyama ridge, the forearc of the subduction system, is well-developed except next to Taiwan; there 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 to be the most notable.

The southern Taiwan zone terminates in the vicinity of 23^{O}N latitude against the collision regime of Central Taiwan. Above this zone is the accretionary wedge, of which the Hengchun Peninsula is a part; it is clearly mapped in two marine geophysical studies, the 1992 Ocean Researcher 1/Moana Wave (Reed 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^{O}N, 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 (Fig. 2) and the offshore tectonics confirm the subduction. The maximum depth of earthquakes in this zone reaches about 150 km, *vs* the more than 200 km 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 shallow part of the much of the Central Range is clearly a zone of low seismicity, at the corresponding depth under the Peninsula, the seismicity is quit 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 South American, the Alaskan, the Kuriles, and the Japan zones 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. But how big can the northern subduction zone earthquake be? Ruff (1996) summarized the seismogenic structures as shown in Fig. 4. Considering the shallow interplate thrusts, which 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 by the horizontal rupture length. For the northern Taiwan zone, a major tectonic feature, the Gagua Ridge, is being subducted roughly along the 123^{O}E longitude; judging from the dent it created in the Ryukyu arc (Lallemand, personal communication, 1996) as it engages the Ryukyu system, it will probably prevent the rupture in the shallow thrust zone near Taiwan to extend beyond it and thus places a limit on the size of possible rupture. Fig. 5 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 an magnitude 7-8 event. That such size event is possible is shown by the occurrence of the 1920 event. Incidentally the 1966 M_W=7.8 event was actually a subduction event, judging from its depth. It is fortunate that only a small portion of the potential fault plane underlies eastern Taiwan. But the long distance effect in Taipei at the period of a few seconds, similar to that of the 1985 Mexico earthquake, should be considered.

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, the Taiwan zones are at the end of zones. With the Eurasian plate subducting the Philippine Sea plate at about 4.5 cm/yr, an average rate measured by GPS (Yu and Chen, 1995) for the motion of Hengchun Peninsula over the Philippine Sea plate, a magnitude 6.5 earthquake with a slip of 1.5 m, say, will have a recurrence rate of about 30 years. The Philippine Sea subduction zone under northern Taiwan and offshore northeast of Taiwan most probably involves deformation. If taken at the apparent value of about 2 cm/yr (component of the Philippine Sea plate motion vector in the direction of subduction), an earthquake with 3 m displacement will recur every 150 years. The recurrence period could be shorter if the plate velocity is increased through intraplate deformation and escape" (Wu, 1978). In this respect it is interesting to note that the apparent relative plate motion is faster in the southern zone than in the northern zone, but the seismicity is much lower in the southern zone than in the northern zone. This apparent contradiction can be understood in terms of intraplate plate deformation of the Philippine Sea plate in the northern zone.

6 Discussion

In this paper we have discussed the seismogenic structures of Taiwan that have either not been heretofore discussed or discussed fully. These include both plate boundary and intraplate types. The other important structures that are well-known include the Longitudinal Valley fault system (LVFS), which is a boundary of great plate tectonic significance, and the shallow intraplate faults that were activated during the 1906 Chiayi and the 1935 Hsinchu earthquakes in western Taiwan. It is also interesting to note that the intermediate depth events in the northern subduction could led to damages as did the 1909 earthquake under Taipei. The LVFS, of course, is not a simple strike-slip fault; it involves strain partitioning in terms of both oblique strike-slip and thrust faulting (Wu et al., 1989). 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.

There are several ways in which the seismogenic structures discussed 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 from a "mainshock". For general estimates one can also use world-wide accelerograms from similar structures and similar 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 from tectonics, which is an integrative topic that employs crustal structures, gravitational data, focal mechanisms, surveying, surface geology as well as seismicity. Deductions based on tectonics is therefore more general than those based on seismicity alone. It is conceivable that we shall be able to build a numerical model, corresponding to the conceptual one we have described, that is based on the physics of the problem, including constitutive relations for the materials involved, the boudary conditions that are implied in the conceptual model, the ambient conditions, fluids as well as the stress field. Then a more systematic and rational view of the dynamics of the earthquake problem as a function of time can be pursued.

7 Conclusion

The planning and execution of seismic hazard reduction procedures is a long term process. Based on the 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 scenario 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, retrofit on existing structures may be effective. On the other hand, aseismic design for future major structures, bridges, tall buildings, and lifelines and the formulation of land-use policy can 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 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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Figures

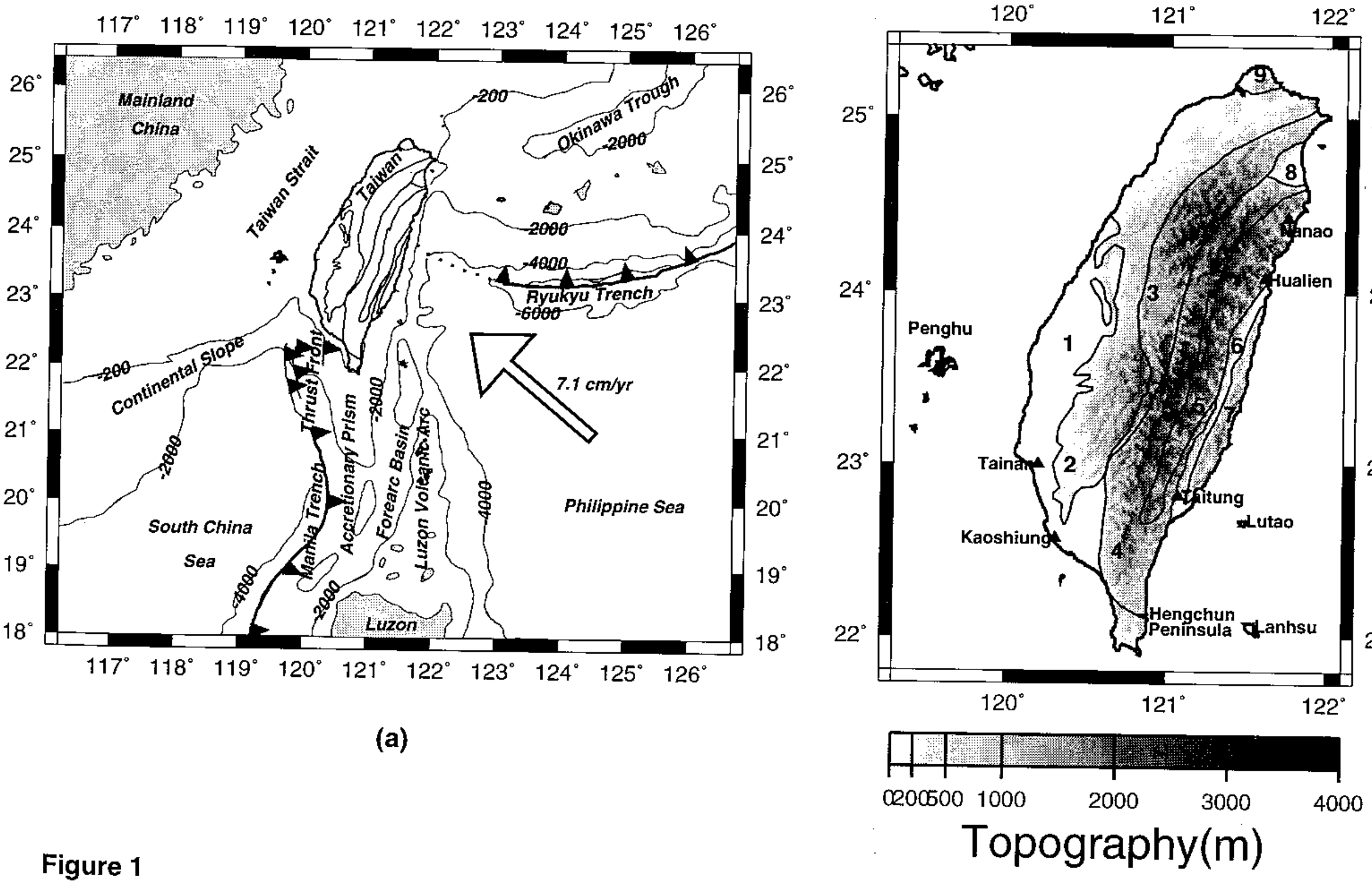
Figure 1. (a) The overall plate tectonic environment of Taiwan (Rau and Wu, 1995). (b) Main geologic boundaries and physiographic units (Ho, 1988): 1. Western Coastal Plain (Quaternary), 2. Western Foothills (Plio-Pleistocene), 3. Hsueshan Range (Eocene-Miocene), 4. Backbone Range (Eocene - Miocene), 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).

Figure 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. The NWW motion of the Philippine Sea plate led to both northward subduction of the Philippine Sea plate (a) and the collision of the lithospheres 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.

Figure 3. (a) map view of events in a NW-SE belt of seismicity, with focal mechanisms plotted for a number of events. (b) cross-section of same events showing the depths of events.

Figure 4. The seismogenic features of a subduction system. 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.

Figure 5. Harvard CMT solutions of $M_W > 5.6$ earthquakes from 1977.1 to 1996.2. Note that a gap exists between the normal faulting and shallow thrust events. Could this be the rupture area for a future interplate event?


117° 118° 119° 120° 121° 122° 123° 124° 125° 126°
18° 19° 20° 21° 22° 23° 24° 25° 26°
Mainland China
Taiwan Strait
Taiwan
Okinawa Trough
Ryukyu Trench
Continental Slope
Thrust Front
Manila Trench
Accretionary Prism
Forearc Basin
Luzon Volcanic Arc
Luzon
South China Sea
Philippine Sea
7.1 cm/yr
-200
-2000
-4000
-6000
4000
Penghu
Tainan
Kaoshiung
Hualien
Nanao
Taitung
Lutao
Lanhsu
Hengchun Peninsula
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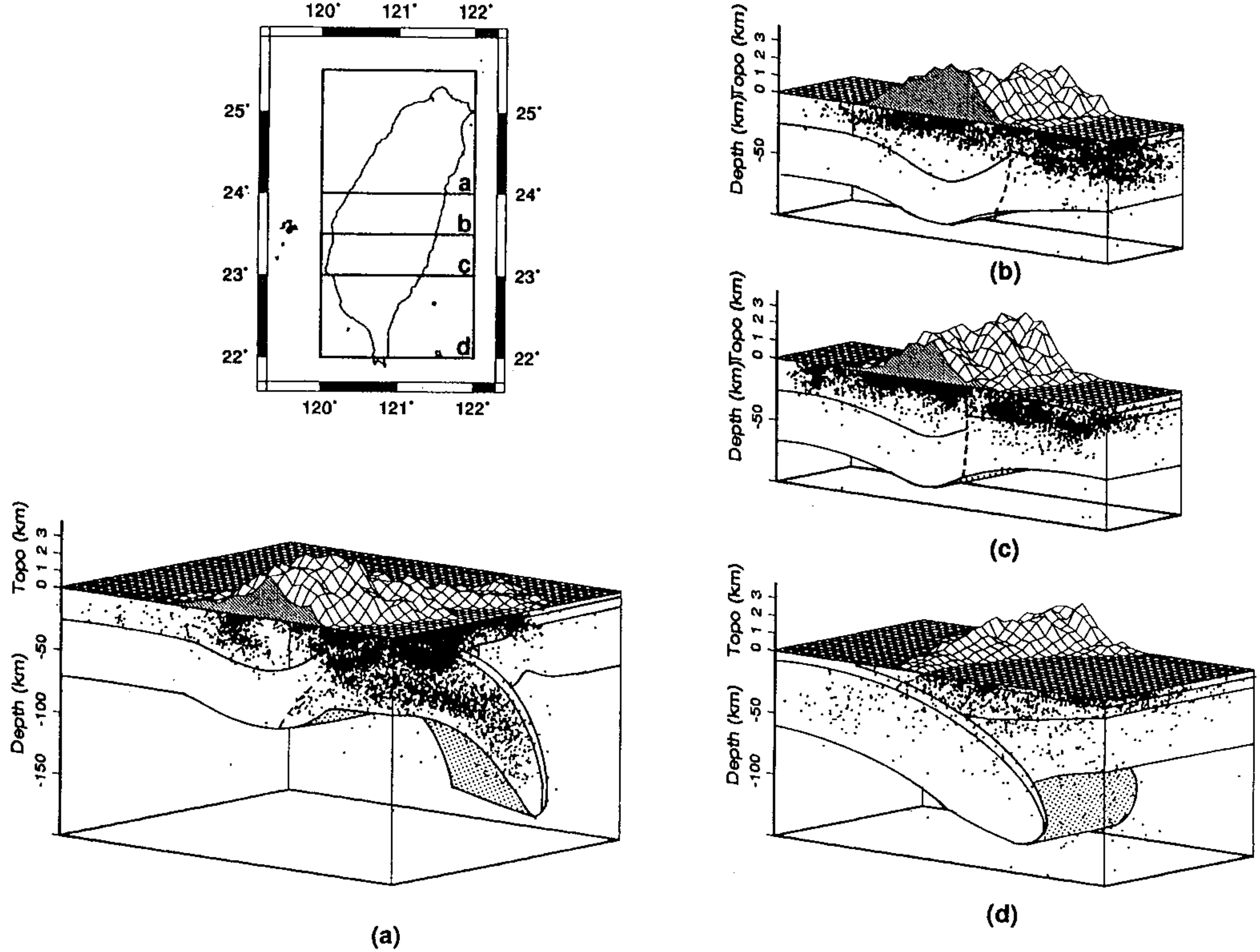
0 200 500 1000 2000 3000 4000
Topography(m)

(a)

(b)

Figure 1


120°
121°
122°
25°
24°
23°
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a
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Topo (km)
Depth (km)
Depth (km)Topo (km)
3
2
1
0
-50
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(a)
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(c)
(d)

FIGURE 2

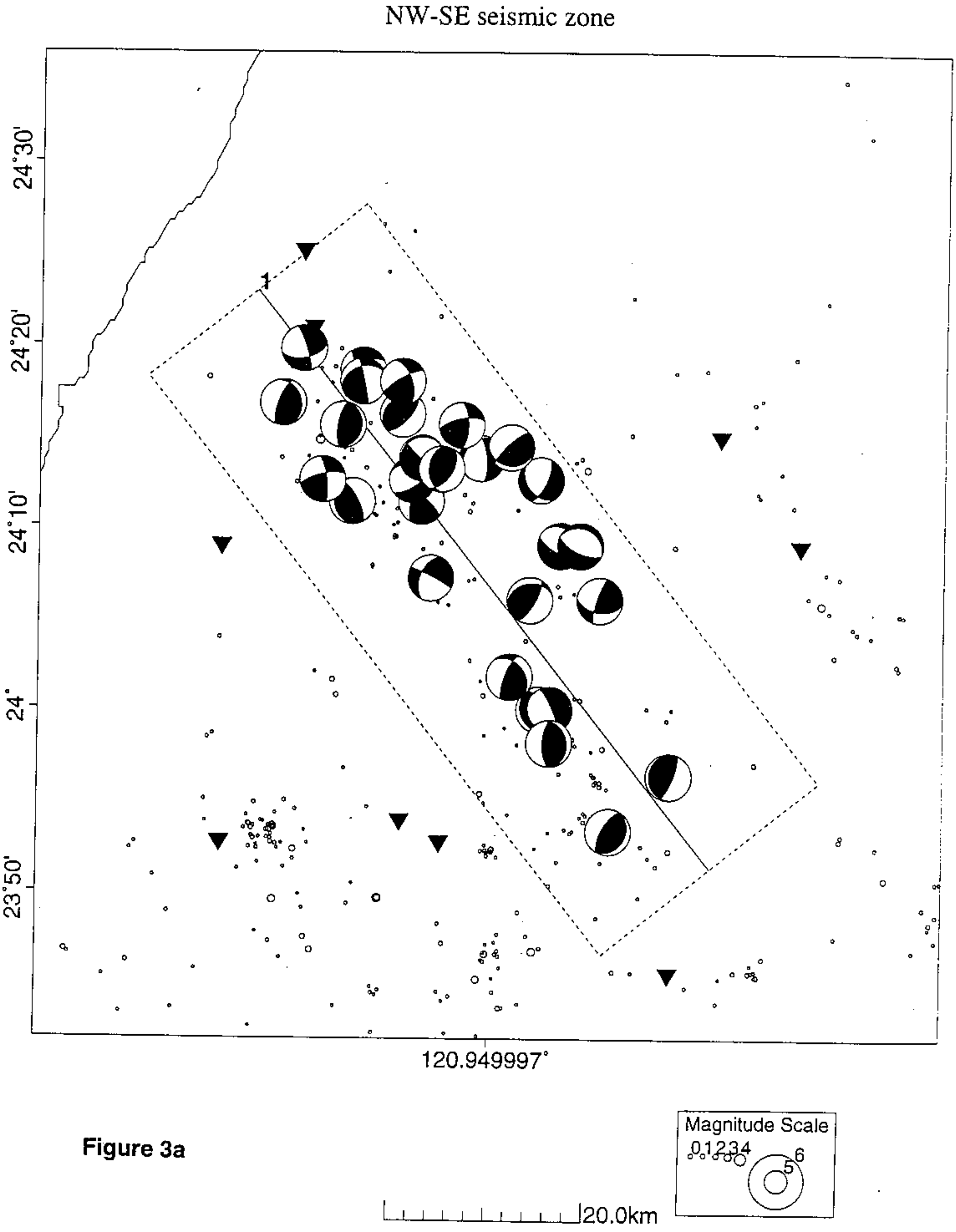
NW-SE seismic zone

Figure 3a

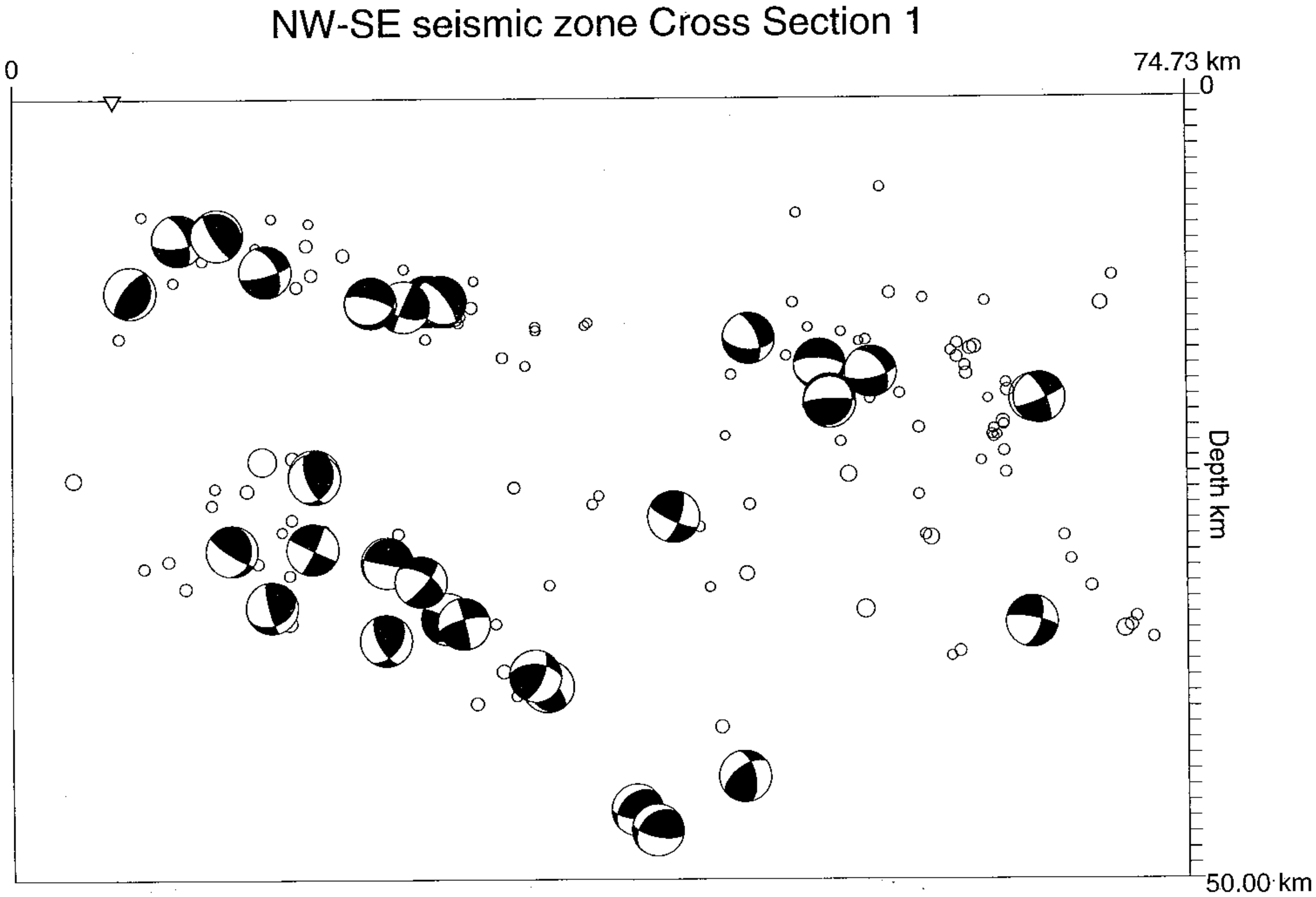
NW-SE seismic zone Cross Section 1

Figure 3b

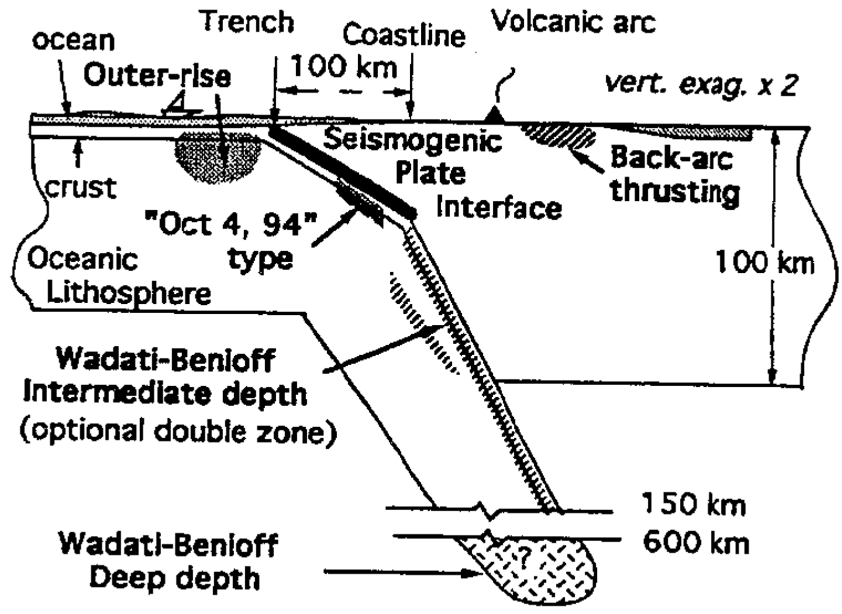
ocean
Trench
Coastline
Volcanic arc
Outer-rise
100 km
vert. exag. x 2
crust
Seismogenic
Plate
Interface
Back-arc
thrusting
"Oct 4, 94"
type
Oceanic
Lithosphere
100 km
Wadati-Benioff
Intermediate depth
(optional double zone)
150 km
600 km
Wadati-Benioff
Deep depth
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Figure 4

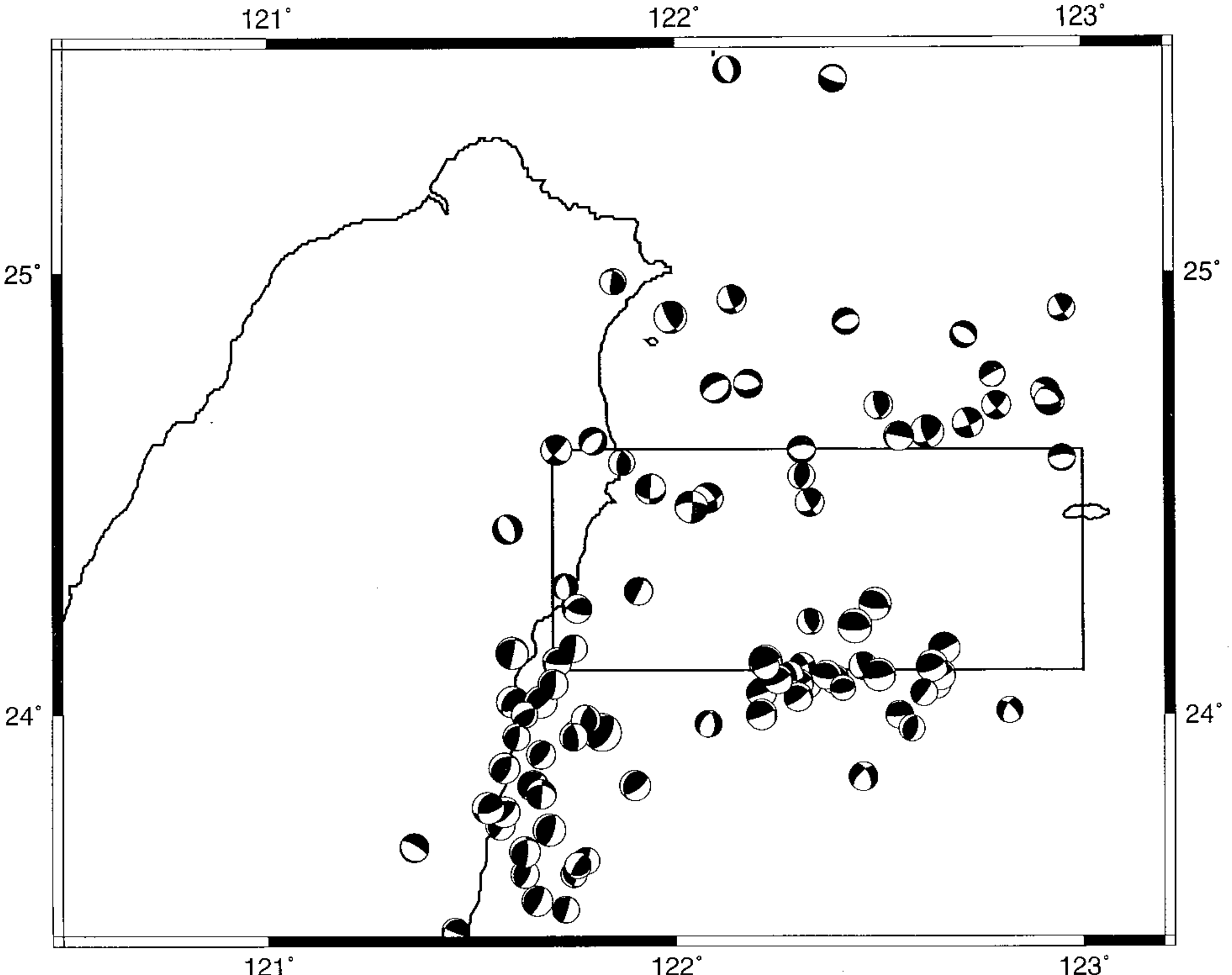

Figure 5