Depth of Seismicity in the Taiwan Orogen and its Relationship to Lithospheric Rheology

Ruey-Juin Rau[1] **and Francis T. Wu**[2]
(饒瑞鈞,吳大銘)
[1] **Institute of Earth Sciences, Academia Sinica, Taiwan**
[2] **Department of Earth Sciences, SUNY, Binghamton, NY 13902, USA**

Abstract

In early 1991, the Central Weather Bureau (CWB) has upgraded its Taiwan Seismic Network (TaiSeiN). It now has 75 digitally recording three-component short-period seismic stations, with inter-station spacing on the order of 10-30 km. Besides providing improved detection, the digitally recorded data also have excellent relative timing accuracy. Between January 1991 and July 1996, 57,119 earthquakes were recorded. By first deciphering the 3-D velocity structures under the island, the relocated hypocenters can then be used for studying fundamental physical properties of the lithosphere under Taiwan. In our study, $M_L \geq 2.7$ earthquakes with CWB Seismological Center defined hypocentral solution qualities of A and B are tomographically relocated. Regional variations of the earthquake distributions in the Taiwan orogen are determined based on the relocated events with focal depth ≤ 50 km. Four regional earthquake distribution patterns are recognized. First, a prominent double-layered seismicity structure is observed in western Taiwan between 23.8 and 24.4°N with two zones at the depth ranges of 5-15 and 23-40 km; the depth range of 15-23 km is essentially aseismic. Second, earthquakes occur in the upper 20 km with a major concentration in the upper 15 km between 22.8 and 23.8°N in southwestern Taiwan. Third, earthquakes occur noticeably less frequently in the middle part of the eastern Central Range and the Peikang basement high. Finally, earthquakes occur mainly in the depth range of 15-40 km between 22.6 and 22.8°N in southern Taiwan. These observations are generally consistent with the conventional lithospheric rheological models and are probably controlled by the thermal regime in the crust and by lithology; these are of fundamental importance to the study of the Taiwan orogeny and seismic risks.

1 Introduction

The knowledge concerning mechanical properties of crustal rocks is important for understanding the geological processes at depth. On the one hand, triaxial laboratory experiments under high confining pressure and temperature appropriate for the crust are carried out to decipher the basic rock behavior (for a review, see Kohlstedt et al., 1995). It is found that for a normal geothermal gradient, rocks behave brittly at shallow depths (h < 15-20 km); for continental rocks, the ductility becomes dominant in the lower crust (15-20 km) and the Moho, as controlled by the quartz flow law. Below Moho, brittle behavior resumes until flow of olivine occurs and thereby renders the rocks ductile again. Seismic radiation occurs in the depth range in which the rocks behave brittly. On the other hand, various earthquake distribution patterns are observed in various parts of the world. Chen and Molnar (1983) compiled a list of focal depths of well-located intracontinental and intraplate earthquakes, and concluded that in continental regions seismicity usually is confined to the brittle upper crust but occasionally occurs also in the stronger uppermost mantle. The presumably weak lower crust, however, appears to be aseismic. By contrast, in oceanic regions, seismicity occurs throughout the thin crust and the stronger upper mantle down to a depth of 60 km (Wiens and Stein, 1983). These observed distributions of seismic foci are in general agreement with the rheological profiles of the lithosphere as determined by the laboratory experiments. Such distributions are often correlated with other physical properties of the lithosphere, such as, thermal structure, lithology, strain rate, and tectonic regime (e.g., Chen and Molnar, 1983; Doser and Kanamori, 1986; Miller and Furlong, 1988; Furlong and Langston, 1990).

In continental regions, although the brittle-ductile-brittle seismic zones (BDBSZ) were reported in areas of continental convergence with thickened crust (Chen and Molnar, 1983), most of the studies on the continents of normal crustal thickness indicate that most of the seismicity concentrate above a depth of ~20 km -- the cutoff depth of seismic activity (e.g., Doser and Kanamori, 1986; Ito, 1990). This discrepancy raises two questions: is the BDBSZ only observed in the thickened lithosphere? If so, what are the possible causes? Or, could BDBSZ exist in all continental lithosphere, but the upper mantle earthquakes occur only infrequently. These questions can be answered by a detailed study of the seismicity pattern in the continental region with a densely spaced seismic network and intense seismic activity. The island of Taiwan is one of the few places in the world that is both intensely seismic and well monitored with a dense seismic network. In this work we shall analyze the seismicity of Taiwan as recorded by the upgraded TaiSeiN. This study will not only greatly improve our understanding on the physical processes of the Taiwan orogeny, but will also provide important constraints on the rheological properties of the continental lithosphere in general.

The patterns of seismicity under and around Taiwan was first studied by Tsai et al. (1977), Wu (1978), Tsai (1986), Roecker et al. (1987), Wu et al. (1989), and Rau (1992). These studies provided a reasonably clear picture of the overall geometry of plate motions in and around Taiwan. Moreover, Wang et al. (1994) studied the shallow earthquakes in the Taiwan region using TTSN data and they attempted to relate depth distribution of earthquakes to the composition, fault zone characteristics, and heat flow in different regions. Having only vertical component at most stations, hence the lack of S-waves, and being an analog system, the TTSN event locations were relatively imprecise in comparison to the upgraded TaiSeiN. In 1991, TaiSeiN was expanded to include 75 three-component stations with the inter-station spacing on the order of 10-30 km. Besides providing improved detection, the digitally recorded data also have excellent relative timing accuracy. Between January 1991 and July 1996, 57,119 earthquakes were recorded (Figure 1); the quantity and quality of the dataset are sufficient for a detailed analysis of seismicity as a function of depth. It is now possible because we have obtained 3-D velocity structures under the island (Rau and Wu, 1995), so that we now can tomographically relocate events to improve the depth resolution (Rau et al., 1996). We are particularly interested in the factors that control the depth distribution of earthquakes. This paper is mainly concerned with the seismicity of the Taiwan orogen that is not directly related to the active subduction.

2 CWB Routine Earthquake Location Results

To provide a basis for comparison with later results we first present the results of 1-D locations obtained in the routine operation of CWB. The program HYPO71 (Lee and Lahr, 1975), in conjunction with the 1-D velocity model derived by Yeh and Tsai (1981), is used. For comparison with our results to be shown later, the events within the network of qualities of A and B from January 1, 1991 to July 31, 1996 are plotted (Figure 1). Quality A locations refer to events recorded at more than 6 stations, having azimuthal gap less than 135°, and the epicentral distance to the nearest station less than the focal depth; for quality B the nearest station is less than twice the focal depth.

Sections **a-d** (Figure 2) show the main features of crustal seismicity. In cross section **a** the western Taiwan seismicity is characterized by a double-layered seismic zone with earthquakes concentrating in the depth ranges of 0-15 km and 20-40 km, respectively. Under the eastern Central Range, a sharp contrast appears between the intense seismicity to the east and nearly aseismic to the west. In cross section **b** the double-layered seismic zone is still discernible under the west-central Taiwan, while in cross section **c** the seismicity becomes a single layer concentrating mainly in the upper 20 km. In both sections **b** and **c** the seismicity under the eastern Central Range and farther east seems dipping to the east. Under the southern Taiwan (section **d**) a east-dipping seismic zone can be seen under eastern offshore and the seismicity under the southwestern Taiwan occurs mainly under a depth of 20 km.

3 Relocation of Earthquakes

In this study we tomographically relocated 2218 selected events, twice as many events as used by Rau and Wu (1995). The events were selected from earthquakes of $M_L \geq 2.7$ having P arrivals recorded at more than 8 stations with gap less than 135°. For most of the earthquakes, the tomographically relocated hypocenters deviate from their initial locations by less than 2 km horizontally and 5 km vertically. To analyze the seismicity pattern the initial and relocated earthquake locations are plotted in cross sections, and the number of events and the seismic energy are plotted as a function of depth for the relocated events (Figures 3-6).

4 Results

Comparisons of the routine CWB locations and our results show that the differences are not significant (Figures 4-6). Thus the depth distributions in Taiwan seismicity can be analyzed with confidence by using only the high quality CWB earthquake data. Four noticeable features can be discerned in cross sections AA' - FF'. First, two distinct seismic zones can be observed in cross section AA' at depth ranges of 5-15 and 23-40 km. The depth range 15-23 km is essentially aseismic. Second, in southwestern Taiwan between 22.8 and

23.8°N, earthquakes occur in the upper 20 km, but concentrate mainly in the upper 15 km. Third, seismicity is clearly low in the middle part of the eastern Central Range and the area of the Peikang basement high. Finally, earthquakes occur mainly at the depth range of 15-40 km between 22.6 and 22.8°N in the southern Taiwan.

In viewing the frequency-depth distributions of earthquakes (Figures 4d-6d) we found that the peaks of the distributions are generally at a depth of ~10 km, and the seismic-aseismic transition zone in the crust is estimated at depths of ~15-20 km, except for that of profile AA'. For the seismic energy-depth distributions shown in figures 4e-6e, however, we found that most of the energy concentrate in the depth range of 10-25 km, except for the double-layered seismic zone of profile AA' and the lower crustal seismic zone of profile FF'.

5 Discussion

The observed earthquake frequency-depth distributions in the western Taiwan are in general agreement with the laboratory experiments predicted continental rheological profile which consists of a brittle upper crust, a ductile lower crust, and a strong and sometimes brittle upper mantle. The crustal seismic-aseismic transition zone at ~15-20 km is interpreted as the brittle-ductile transition zone. For the seismic energy-depth distributions (Figures 4e-6e), because of the fact that most of the energy concentrate in the depth range of 10-25 km, large earthquakes in the western Taiwan appear to originate at or just below the seismic-aseismic (brittle-ductile) transition zone where the shear strength of the fault rocks may have a maximum.

The appearance of the double-layered seismic zone in the northern half of the western Taiwan indicates that the upper mantle of this area is strong and behaves brittly. In contrast, the low level of upper mantle seismicity in the southern half of the western Taiwan leads us to believe that its upper mantle is weak. However, the January 18, 1964 southwestern foothills earthquake (Ms = 6.5) occurred at a depth of 23 km (Wu et al., 1991), which is very close to the Moho depth (25-27 km) (Rau, 1992) there. This 1964 event is large enough to lead us to conclude that the upper mantle under the southwestern Taiwan is also strong; the low seismicity in the uppermost part of the mantle in the recent five and a half years is perhaps time-dependent.

The nearly aseismic zone in parts of the Central Range may be related to the high heat flow and the extrusion of the mid-lower ductile crustal materials which limit the brittle regime to the shallow depth. The low level of seismicity in the Peikang basement high may be resulted from its upheaving basement. On the other hand, the lowering of the seismicity in southern Taiwan is probably caused by the presence of thick, young and unconsolidated mudstone and other sediments in the upper crust. The seismicity observations show the lateral variations of lithospheric strength in the Taiwan orogen. As indicated by the earthquake distributions, the Central Range may behave ductily and is likely to be created by the upward extrusion of the mid- and lower crustal materials. The crustal part of the Central Range may be connected to its source - the lower crust of the western foothills - by the form of flow, where the ductile lower crust separates the brittle upper crust and mantle.

Anomalously high heat flow values (> 5 hfu) have been measured in the Central Range (Lee and Cheng, 1986). It is also reflected by the abundance of thermal springs with temperatures in the range of 90°C. Hydrothermal and/or magmatic factors can contribute to the high heat flow in island arc areas (e.g., Bodri and Iizuka, 1993). Fluid circulation within the crust is certainly an important factor in the thermal model calculations (Barenblatt et al., 1990). Song and Ma (1996) have demonstrated that the anomalously high heat flow in the Central Range can be explained by the groundwater circulation above a depth of ~4 km. However, many of the parameters in the thermal model calculation for the Central Range are very difficult to estimate reliably. At present, the detailed temperature profile under the Central Range remains unknown. Based on the rheological considerations, we believe that the thermal gradient in the Central Range is greater than that in the western Taiwan. Also, if the Central Range was formed by the extrusion of the higher temperature mid-lower crustal materials in the Central Range, then the thermal gradient in the upper part of the crust is expected to be higher than that of the Western Foothills (Rau and Wu, 1995).

Evaluation of the seismic risk of a certain area needs a thorough understanding of its seismogenic zone. In western Taiwan we found that large earthquakes occurred near the base of the crustal seismogenic zone at a depth of ~20 km. This indicates that large events in the western Taiwan could occur as blind faults at depths; the January 18, 1964 western foothills earthquake (Ms = 6.5, depth = 23 km) was an important example. According to the historical records (Fang, 1969), western Taiwan is known for having many destructive events. With only a few known surface ruptures, the potential hazards presented by blind thrusts in the crustal seismic zone of the western Taiwan is especially important. Detailed seismic exploration using artificial and natural sources in the suspected seismogenic zones of the western Taiwan are needed for further seismic risk evaluation.

6 Conclusions

Judging from the seismicity pattern, we have determined the lateral variations of lithospheric strength in the Taiwan orogen. The seismicity in the Taiwan orogen is likely to be controlled by the factors of surface heat flow, crustal structure, and lithology. The transition in the crust from the western foothills to the Central Range is described by the rheological profiles from the brittle-ductile-brittle model to the ductile model. The fact that most large earthquakes in the western Taiwan nucleated at the base of the seismogenic zone draw our attention to the study of the nature of the deep crustal seismogenic zone while evaluating the seismic risk.

7 References

Barenblatt, G. I., V. M. Entov, and V. M. Ryzhik, *Theory of Fluid Flow Through Natural Rocks*, Kluwer, Dordrecht, 395 pp, 1990.

Bodri, B., and S. Iizuka, Earthquake cutoff depth as a possible geothermometer - applications to central Japan, *Tectonophysics, 225*, 63-78, 1993.

Chen, W.-P., and P. Molnar, Focal depths of intracontinental and intraplate earthquakes and their implications for the thermal and mechanical properties of the lithosphere, *J. Geophys. Res., 88*, 4183-4214, 1983.

Doser, D. I., and H. Kanamori, Depth of seismicity in the Imperial valley region (1977-1983) and its relationship to heat flow, crustal structure, and the October 15, 1979, earthquake, *J. Geophys. Res., 91*, 675-688, 1986.

Fang, H., A compilation of historical records of Taiwan earthquakes before the twentieth century, *Selection of Own Writings on Sixtieth Birthday*, 693-737 (in Chinese), 1969.

Furlong, K. P., and C. A. Langston, Geodynamic aspects of the Loma Prieta earthquake, *Geophys. Res. Lett., 17*, 1457-1460, 1990.

Ito, K., Regional variations of the cutoff depth of seismicity in the crust and their relationship to heat flow and large inland-earthquake, *J. Phys. Earth., 38*, 223-250, 1990.

Kohlstedt, D. L., B. Evans, and S. J. Mackwell, Strength of the lithosphere: Constraints imposed by laboratory experiments, *J. Geophys. Res., 100*, 17,587-17,602, 1995.

Lee, C.-R., and W.-T. Cheng, Preliminary heat flow measurements in Taiwan, in *Fourth Circum-Pacific Energy and Mineral Resources Conference*, Singapore, 1986.

Lee, W. H. K. and J. C. Lahr, HYPO 71 (revised): A computer program for determining hypocenter, magnitude and first motion pattern of local earthquakes, *U. S. Geol. Surv. Open-File Rept.*, 113 pp, 1975.

Miller, C. K., and K. P. Furlong, Thermal-mechanical controls on seismicity depth distributions in the San Andreas fault zone, *Geohys. Res. Lett., 15*, 1429-1432, 1988.

Rau, R. J., Flexure modeling and Taiwan tectonics, *masters thesis*, 131 pp, State University of New York at Binghamton, 1992.

Rau, R. J., and F. T. Wu, Tomographic imaging of lithospheric structures under Taiwan, *Earth Planet. Sci. Lett., 133*, 517-532, 1995.

Rau, R. J., F. T. Wu, and T. C. Shin, Regional network focal mechanism determination using 3-D velocity model and *SH/P* amplitude ratio, *Bull. Seism. Soc. Am., 86*, 1270-1283, 1996.

Roecker, S. W., Y. H. Yeh, and Y. B. Tsai, Three-dimensional P and S wave velocity structures beneath Taiwan: deep structure beneath an arc-continent collision, , *J. Geophys. Res., 92*, 10,547-10,570, 1987.

Song, D.-R., and K.-F. Ma, Heat flow, crustal temperature and their tectonic implication in the Central Range of Taiwan, in *Six^th^ symposium for the Geophysics in Taiwan*, 669-678, 1996.

Tsai, Y. B., Seismotectonics of Taiwan, *Tectonophysics, 125*, 17-37, 1986.

Tsai, Y. B., T.-L. Teng, J. M. Chiu, and H. L. Liu, Tectonic implications of the seismicity in the Taiwan region, *Mem. Geol. Soc. China, 2*, 13-41, 1977.

Wang, J. H., K.-C. Chen, and T.-Q. Lee, Depth distribution of shallow earthquakes in Taiwan, *J. Geol. Soc. China, 37*, 125-142, 1994.

Weins, D. A., and S. Stein, Age dependence of oceanic intraplate seismicity and implications for lithospheric evolution, *J. Geophys. Res., 88*, 6455-6468, 1983.

Wu, F. T., Recent tectonics of Taiwan, *J. Phys. Earth, 26*, Supp., S265-S299, 1978.

Wu, F. T., K. C. Chen, J. H. Wang, R. McCaffrey, and D. Salzberg, Focal mechanisms of recent large earthquakes and the nature of faulting in the Longitudinal Valley of eastern Taiwan, *Proc. Geol. Soc. China, 32*, 157-177, 1989.

Wu, F. T., D. H. Salzberg, and R. J. Rau, The modern orogeny of Taiwan, in *TAICRUST Workshop Proceedings*, pp. 49-62, Taipei, Taiwan, 1991.

Yeh, Y. H., and Y. B. Tsai, Crustal structure of central Taiwan from inversion of P-wave arrival times, *Bull. Inst. Earth Sci., Aca. Sinica, 1*, 83-102, 1981.

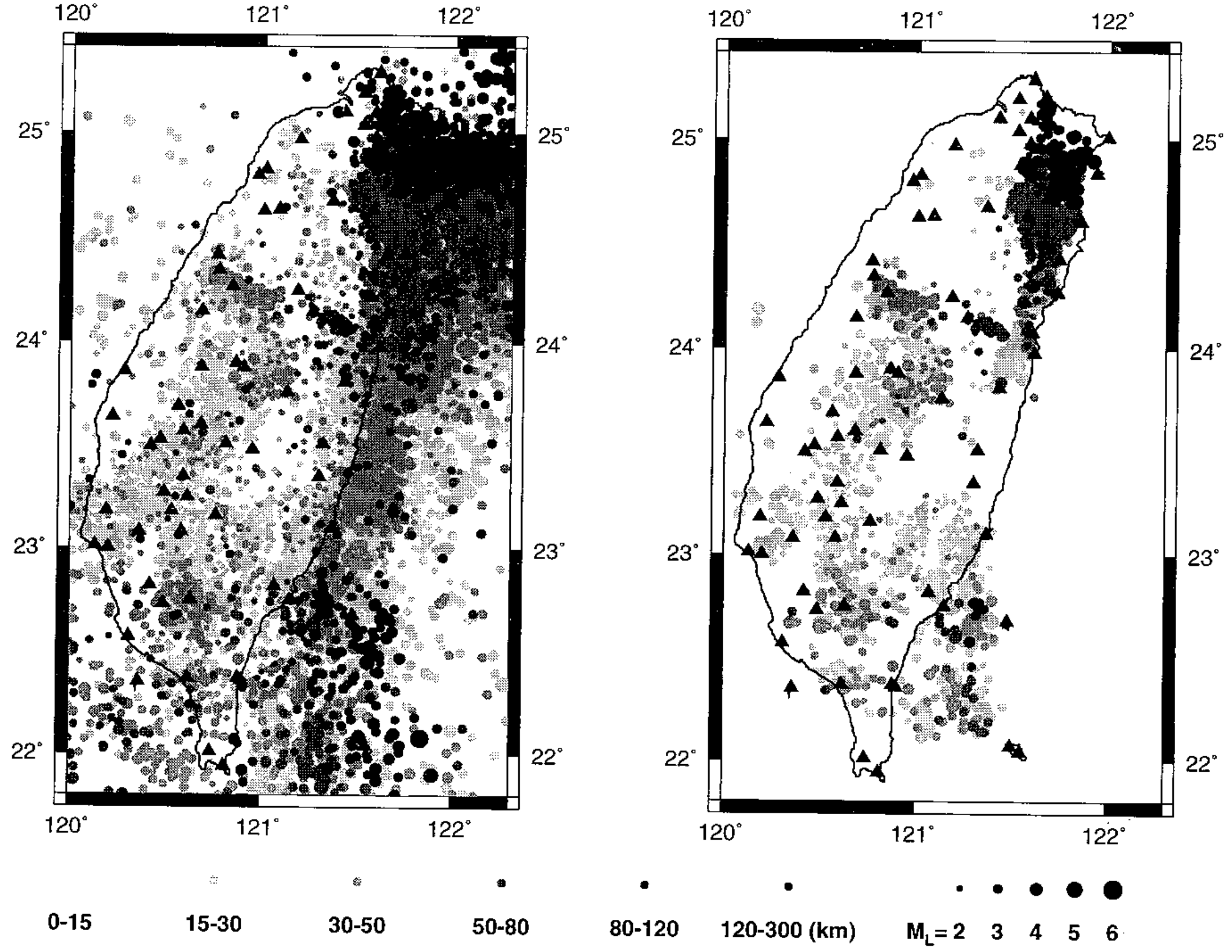

Figure 1. Epicentral maps of Taiwan showing 57,119 (left) and 8525 (right, for quality A and B) epicenters (circles) located by TaiSeiN between January 1, 1991 and July 31, 1996. Seismic stations are shown as solid triangles. Epicenters are coded for both magnitude and depth (scale at bottom).

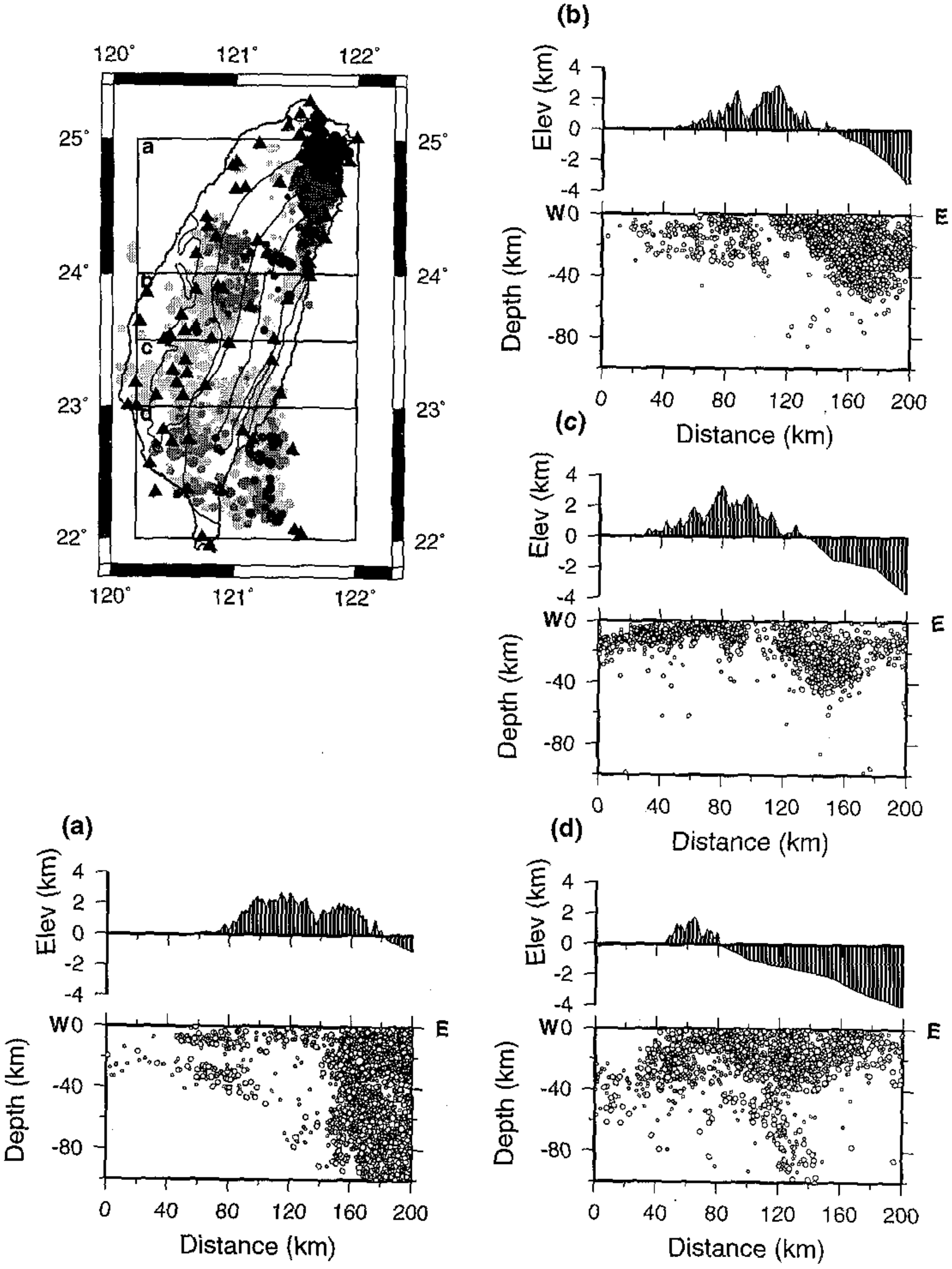

Figure 2. (Upper left) Epicentral map of Taiwan showing 8525 (quality A and B) epicenters (circles) located by TaiSeiN between January 1, 1991 and July 31, 1996. Seismic stations are shown as solid triangles. The locations of seismicity cross sections a-d are shown as boxes. (a-d) The corresponding seismicity cross sections.

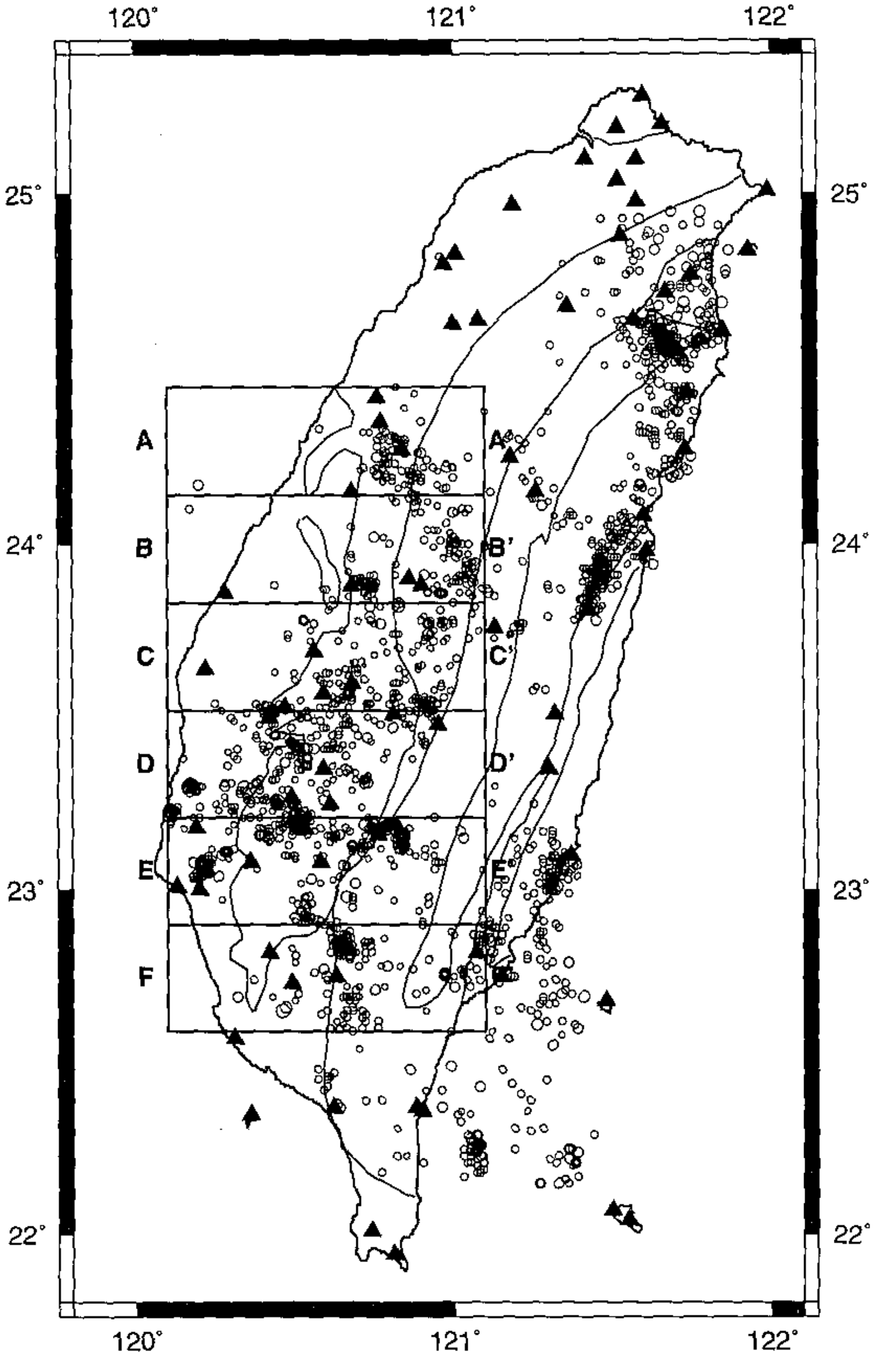

Figure 3. Map of Taiwan showing the locations of the seismic stations (solid triangles) and 2218 tomographically relocated epicenters (91/3-96/7). The geological provinces are separated by solid lines. The locations of the seismic cross sections a-f (figures 4-6) are shown as boxes.

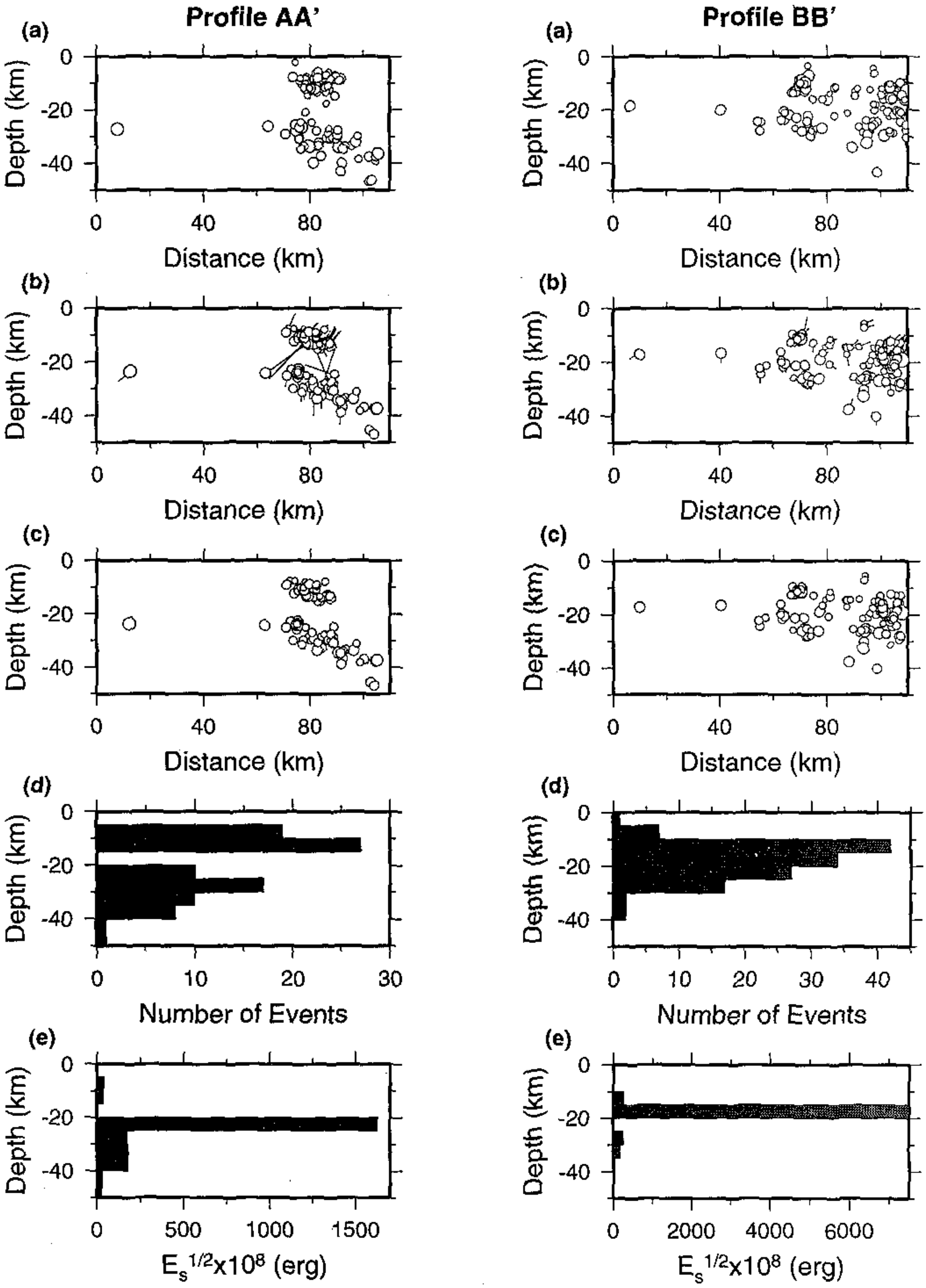

Figure 4. Seismicity cross sections of profiles AA' and BB'. (a) Initial epicentral locations. (b) Epicentral shifts from initial (dots) to relocated (circles) locations. (c) Relocated epicentral locations. (d) Number of events as a function of depth. (e) Seismic energy as a function of depth.

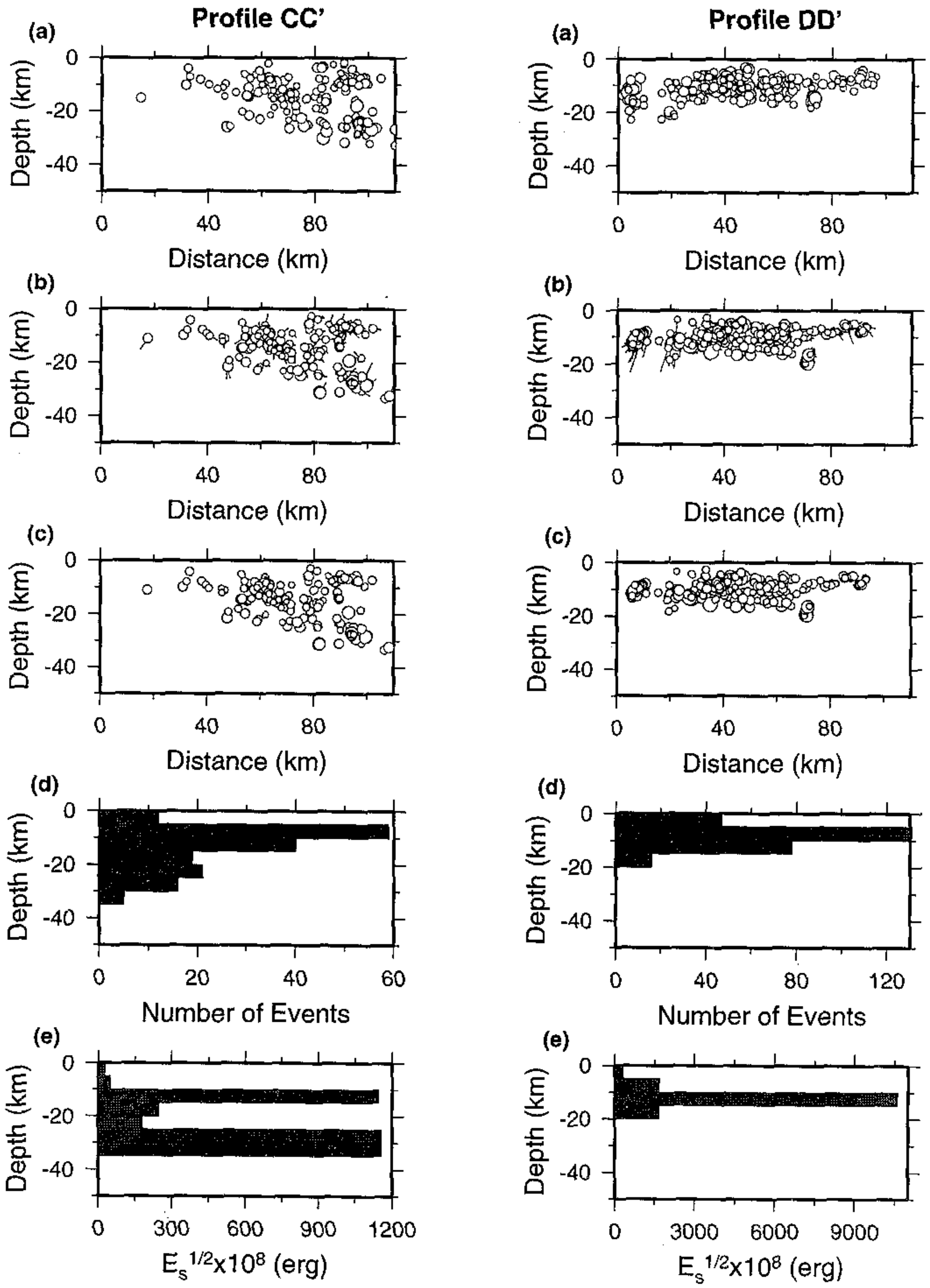

Figure 5. Seismicity cross sections of profiles CC' and DD'. (a) Initial epicentral locations. (b) Epicentral shifts from initial (dots) to relocated (circles) locations. (c) Relocated epicentral locations. (d) Number of events as a function of depth. (e) Seismic energy as a function of depth.

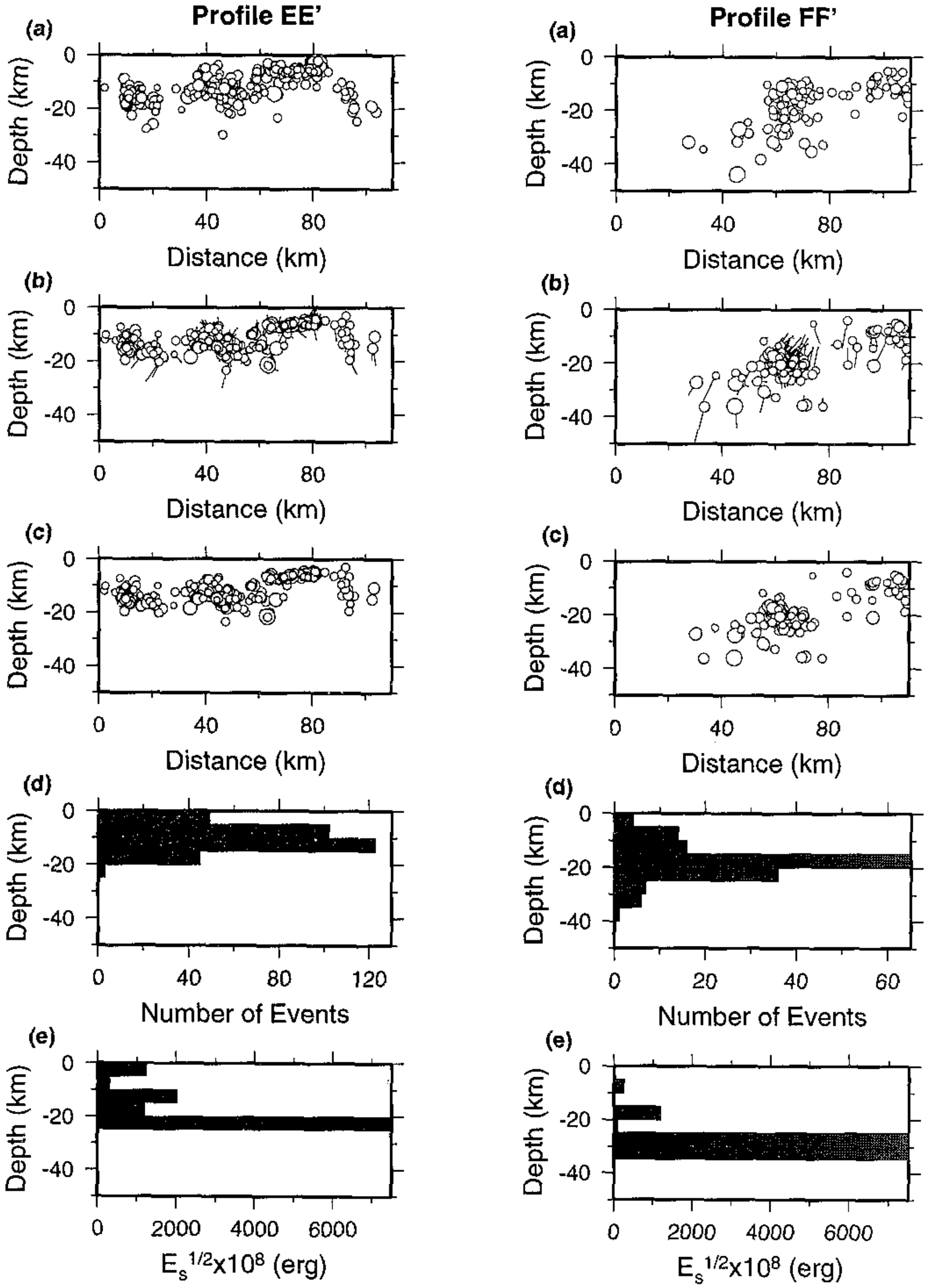

Figure 6. Seismicity cross sections of profiles EE' and FF'. (a) Initial epicentral locations. (b) Epicentral shifts from initial (dots) to relocated (circles) locations. (c) Relocated epicentral locations. (d) Number of events as a function of depth. (e) Seismic energy as a function of depth.