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SUBSURFACE STRUCTURE OF LIJIANG BASIN, YUNNAN CHINA AS RELATED TO DAMAGE DISTRIBUTION CAUSED BY THE M7.0 LIJIANG EARTHQUAKE OF FEBRUARY 3, 1996

J AKAMATSU[1], K NISHIMURA[2], M NAKAMURA[3], M KOMAZAWA[4], L JIANG[5], K LI[6] And Q LUO[7]

SUMMARY

The 1996 Lijiang Earthquake of M7.0 brought serious damage to Lijiang basin. Its seismogenic fault is considered to be the Xueshan fault lying along the western edge of the basin. However, anomalous distribution of severe damage to wooden houses and RC buildings was observed: the most severely damaged zone was located 1.5--2 km far from the basin edge, and the degree of damage remarkably changed place to place along the Lijiang-Jianchuan fault zone, which crosses the southern part of the basin. To reveal the subsurface structure of the basin, array observation of microseisms (long-period microtremors), seismic refraction prospecting across the basin and gravity survey were carried out. As a result, it was found that, (1) the bedrock subsides steeply by 400 m or more at both west and east basin edges, the bedrock subsidence at the west edge seems to be related to the Xueshan fault, (2) the depth to bedrock is more than 1,200 m in the central part, and (3) the Lijiang-Jianchuan fault zone brings no steep relief of bedrock implying a strike-slip type. The fault zone seems to have many sub-faults forming block structure.

In conclusion out of the results, the irregular configuration of bedrock related to the faults and the block boundaries characteristic of the fault zone are considered to have affected strongly the ground motions during the earthquake, and consequently the anomalous distribution of damage.

INTRODUCTION

The M7.0 Lijiang Earthquake of February 3, 1996, brought serious damage to Lijiang Naxi People Autonomous County, northwest Yunnan Province, China. The extents of damage are as follows: 309 death toll, 17,057 injured including 4070 moderately or severely injured, 1,186,000 damaged rooms (420,000 collapsed), and total monetary loss of US740 million. The seismogenic fault is considered to be Xueshan fault with north-south strike lying along the western edge of the Lijiang basin [Nakamura et al., 1997]. In the basin, however, anomalous distribution of severe damage to wooden houses and RC buildings was observed: (1) the most severely damaged zone was located 1.5--2 km far from the basin edge, whereas the damage was moderate or even light near the Xueshan fault [Akamatsu et al., 1997a], and (2) there was a remarkable change in the degree of damage near along the Lijiang-Jianchuan fault zone which crosses the southern part of the

[1] *Disaster Prevention Res. Inst., Kyoto University, Japan, E-mail: akamatsu@drs.dpri.kyoto-u.ac.jp*
[2] *Department of Informatics, Okayama University of Science, Japan, E-mail: nisimura@big.ous.ac.jp*
[3] *Earthquake Research Institute, University of Tokyo, Japan, E-mail: nakamura@wso.eri.u-tokyo.ac.jp*
[4] *Geological Survey of Japan, Japan, E-mail: koma@gsj.go.jp*
[5] *Seismological Bureau of Yunnan Province, P.R.China, E-mail: lequn.jiang@263.net*
[6] *Seismological Bureau of Lijiang Prefecture, P.R.China*
[7] *Institute of Structural Theory, Tongji University, P.R.China, E-mail: luo@mail.tongji.edu.cn*

basin in the NE-SW direction [Jiang, 1997]. It should be noted that, nearly the same anomalous intensity distribution was observed during the 1951 Jianchuan Earthquake of M6.3, whose epicenter and seismogenic fault were different from those of the 1996 Lijiang Earthquake [Jiang et al., 1999].

Our objective is to investigate the subsurface structure in the basin, mainly the configuration of bedrock related to the faults, and to discuss its effects on the damage distribution. For this, Japan-China joint-research group carried out array observations of microseisms (long-period microtremors), small-scale refraction experiments, large-scale refraction prospecting across the basin, and gravity survey.

2. THE 1996 LIJIANG EARTHQUAKE

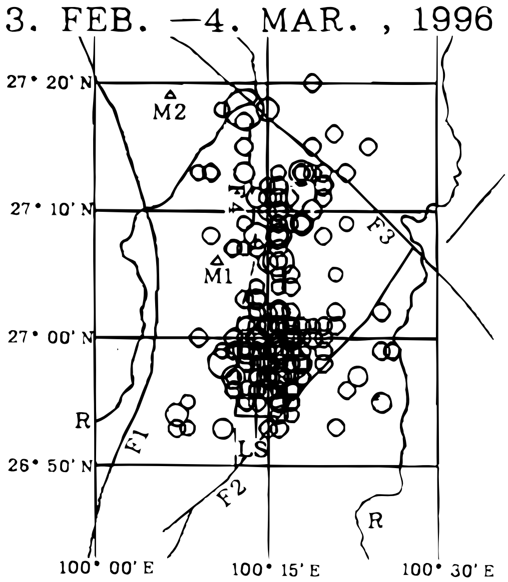


Figure 1 Epicenters of the 1996 Lijiang Earthquake sequence. F2: Lijiang-Jianchuan fault, F4: Xueshan fault.

Fig. 1 shows the epicenters of the earthquake sequence. The epicenter of main shock was located about 40km north of Lijiang City [27.34°N, 100.28°E; Nakamura et al., 1997] and its rupture propagated from north to south for about 40km long [Kikuchi, 1996]. The largest aftershock of M6.0 occurred near the southern end of rupture area. The aftershocks were mainly located on the east of the Xueshan fault. From the direction of rupture and the aftershock distribution, the seismogenic fault was considered to lie under the Xueshan fault. Fig. 2 shows the distribution of intensity in MM scale. The Lijiang basin is included in an area of intensity 9.

It is interesting to compare the distribution of intensity with that caused by the Jianchuan Earthquake of M6.3 ocurred on Dec. 21, 1951. The distribution of intensity for the 1951 Jianchuan Earthquake

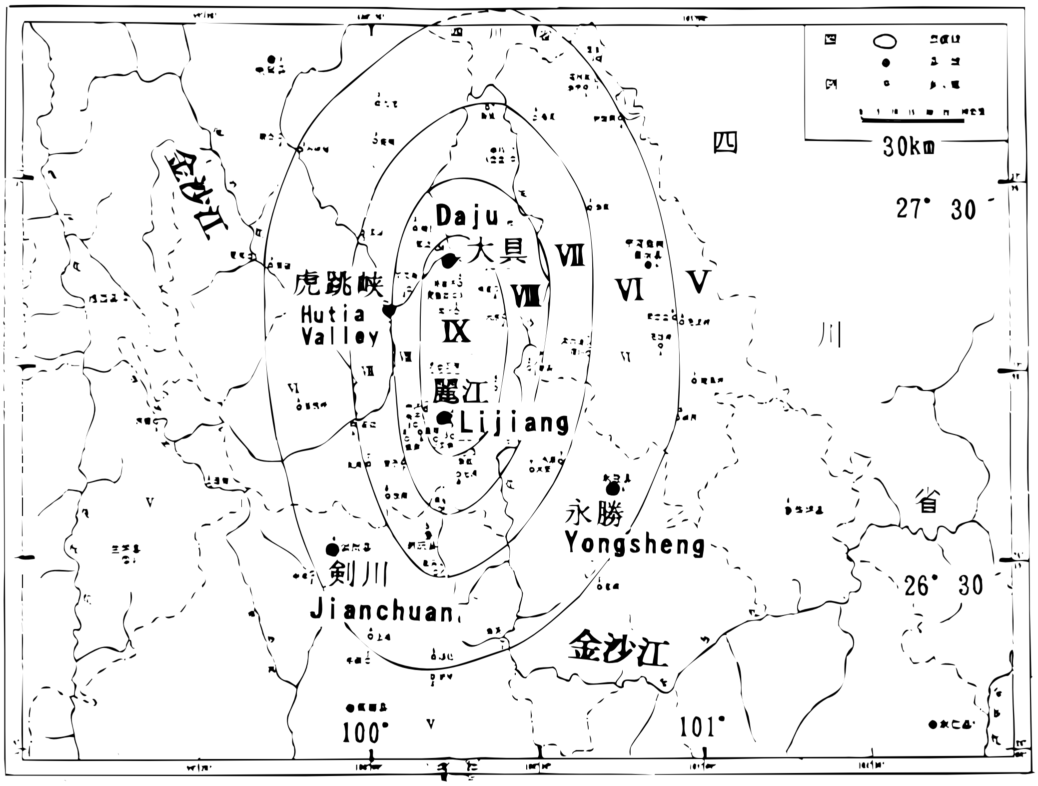


Figure 2 Distribution of seismic intensity for the 1996 Lijiang Earthquake (MM).

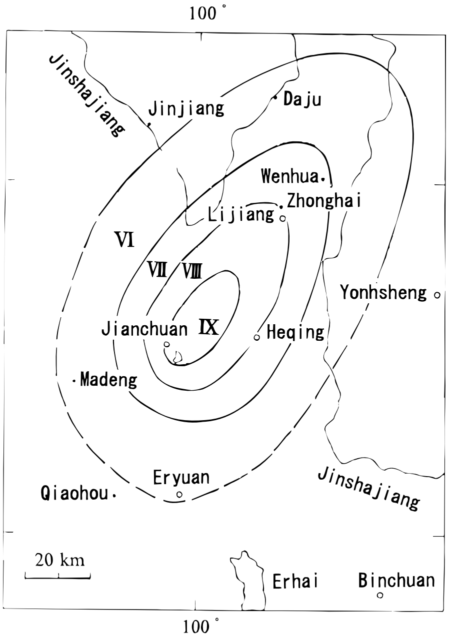


Figure 3 Distribution of seismic intensity for the 1951 Jianchuan Earthquake (MM).

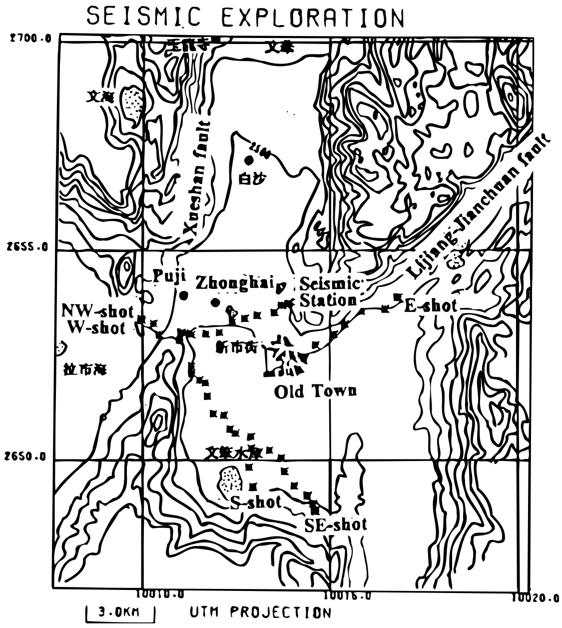


Figure 4 Topographic map of Lijiang basin, showing the location of seismic exploration profiles.

is shown in Fig. 3. Its epicenter was located at 26.4°N, 99.9°E, about 50 km southwest of Lijiang City. Taking account of the shape of the isoseismal lines and the location of epicenter, the rupture seems to have propagated northeastward along the Lijiang-Jianchuan fault. The intensity of the Lijiang basin was assigned at 7 to 8.

3. GEOLOGY AND ANOMALOUS INTENSITY DISTRIBUTION IN LIJIANG BASIN

Fig. 4 shows the topography of the basin. The basin is about 30 km long in the north-south direction, and 5 km wide in the northern part and about 10 km wide in the southern part. The altitude of the basin is about 2,400 m in the southern part, increasing gradually up to 2,800 m toward north. The surface geology consists mainly of the glacial deposits of Pleistocene in the northern part, and of Alluvial or lake deposits in the central and southern parts. The Xueshan fault with north-south strike lies along the western edge of the basin, and the Lijiang-Jianchuan fault with NE-SW strike crosses the southern part of the basin.

Although the whole Lijiang basin was included in an area of intensity 9, anomalous intensity distribution was observed as shown in Fig. 5 [Jiang, 1997]. The notable features are as follows: (1) the highest intensity of 10 is observed at Zhonghai Village, which is located about 1.5 km far from the west basin edge, and a belt-like zone of higher intensity (8–9) extends from north to south along the edge, whereas the intensities near the western margin of the basin such as Puji Village were remarkably low (6–7); (2) the intensity is relatively high changing place to place along the Lijiang-Jianchuan fault zone. It is very interesting that, the most severely damaged area is not located

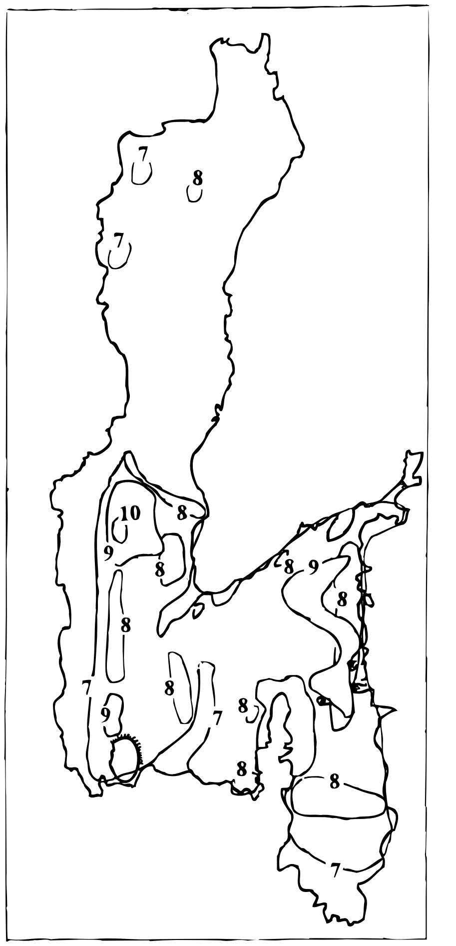


Figure 5 Distribution of seismic intensity in Lijiang basin for the 1996 Lijiang Earthquake.

near along the seismogenic Xueshan fault of the 1996 Lijiang Earthquake. In addition, it should be noted that, nearly the same intensity distribution in the basin was observed for the 1951 Jianchuan Earthquake; for example, the intensity of Zhonghai Village was up to 10, whereas there was no obvious damage in Puji Village located at the west margin.

Table 1 Layer model for phase velocity obtained from microseism analysis

layer	V_p (km/s)	V_s (km/s)	ρ (t/m^3)	H (km)
1	1.5	0.3	1.7	0.17
2	2.0	0.85	1.9	0.15
3	2.5	1.5	2.2	0.5
4	6.0	3.4	2.7	-

4. SUBSURFACE STRUCTURE IN LIJIANG BASIN

4.1 Configuration of Bedrock Inferred from Microseisms

Microseism observations were made for analysis on the basis of 2sSPAC method [Morikawa et al., 1998] and H/V. Basic idea for studying the configuration of bedrock is (1) estimation of velocity structure from the dispersion of Rayleigh waves with 2sSPAC method in the array, and (2) estimation of depth to bedrock at each site with H/V using the velocities obtained from 2sSPAC method. The resultant structure is shown in Table 1. The depth to bedrock is estimated about 820 m. Fig. 6 shows the distribution of peak-period (T_p) for the fundamental mode of H/V. T_p of the fundamental mode is considered to reflect the depth to bedrock [Lachet and Bard, 1994], and can be modeled by Haskell method for incidence of SV waves, provided that the impedance ratio between soil sediments and bedrock is large. In the Lijiang basin, T_p of 1.0, 3.0 and 4.5 s corresponds to the bedrock depth of 0.4, 0.9 and 1.25 km, respectively. As a result, combined analysis of 2sSPAC and H/V shows: (1) The bedrock subsides steeply by more than 400 m both at the east and west basin edges. The steep subsidence at the west basin edge seems to be related to the Xueshan fault; (2) The depth to bedrock reaches up to 1,200 m or more in the central part; (3) The Lijiang-Jianchuan fault, crossing the southern part of the basin, appears not to bring steep bedrock relief.

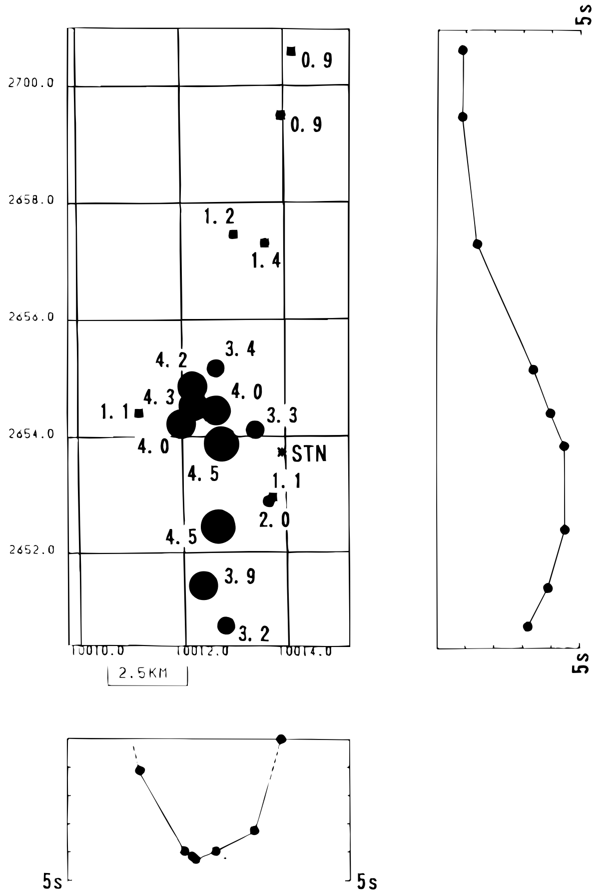
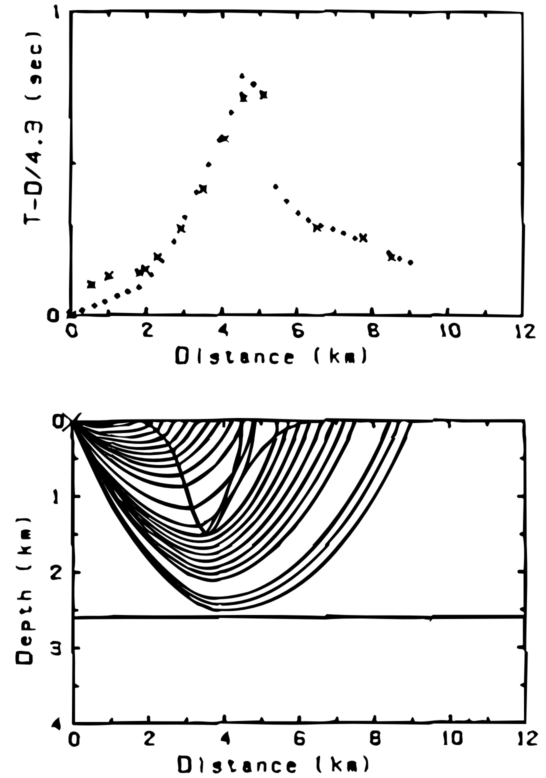


Figure 6 Spatial distribution of peak period in H/V in Lijiang basin. Distribution along N-S and E-W directions are shown.

4.2 2D modeling from Seismic Refraction Prospecting

Large-scale seismic prospecting was carried out with 20 sets of radio-controlled seismographs across the basin: E-W profile crossing the center of the basin and NW-SE profile crossing perpendicularly the Lijiang-Jianchuan fault, as shown in Fig. 4. Structural model along the profiles were obtained using 2D seismic ray-tracing method developed by Cerveny et al. [1977] to calculate theoretical seismic ray and travel time. We assume that P-wave velocity of bedrock increased linearly with depth, from 3.5 km/s at the top of bedrock to 5.5 km/s at 2–3 km deep interface. P-wave velocity in the sediments was also assumed to increase linearly from 1.5 to 2.5 km/s, taking account of the results of 2sSPAC analysis of microseisms. Fig. 7 shows a model along the E-W profile with W shot. Along the E-W profile, the bedrock exhibits rather symmetric configuration with steep subsidence across the east and west edge of the basin. The depth to bedrock reaches 1,500 m or so in the



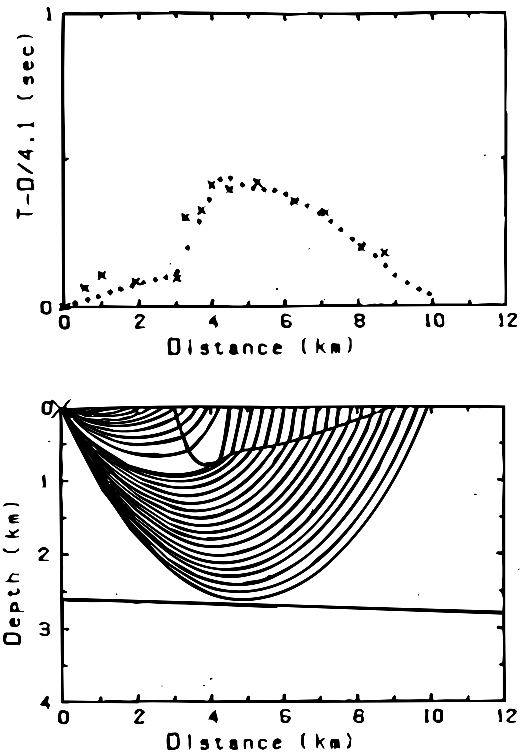


Figure 7 Comparison between observed (×) and calculated (•) P-wave travel times from W-shot for E-W profile (upper panel), and corresponding structural model and ray diagram (lower panel).

Figure 8 Same as figure 7, but from NW-shot for NW-SE profile.

central part of the basin, where the depth was estimated to be 1,200 m or more from the analysis of microseisms. Fig. 8 shows a model for NW-SE profile with NW shot. Along the NW-SE profile, the bedrock subsides fairly steep up to 700 m across the west edge of the basin, probably related to the Xueshan fault. The gradual decrease in depth toward the southeast implies that the displacement across the Lijiang-Jianchuan fault is mainly of strike-slip type.

4.3 3D modeling from Bouguer Gravity Anomaly

The gravity measurements were carried out at about 130 sites, mainly in the central and southern parts of the basin. The location and the altitude were determined by differential GPS with sufficient accuracy. Terrain correction and Bouguer correction within 60 km were made to obtain the Bouguer gravity anomaly. As the difference in altitude among the sites was too small to estimate the proper density both for the terrain and Bouguer corrections, the correction density was given appropriately. Fig. 9 shows the distribution of depth to bedrock of a density model for the central and southern parts of the basin using the inversion method of Komazawa [1984], with an assumption that the densities for the sediments and the bedrock are 2.0 and 2.5 gr/cm^3, respectively. There is a deep trough trending the north-south direction in the central part: the maximum depth to bedrock reaching up to 2,200 m in the central part, and an another subsidence of bedrock up to 2,000 m. From the trough, the depth to bedrock uplifts rapidly towards both west and east basin edges, but gradually towards the south and southeast basin edges. The mountain areas on the south and the east of the basin appear to be covered by a sedimentary layer of a several hundred meters, which results from insufficient constraint caused by the scarce observation sites in the mountain area. The absolute value of depth to bedrock is different from those obtained from microseisms or seismic prospecting, showing the necessity of re-examination of the correction densities, for which additional measurement should be made. However, the model for density distribution shown in Fig. 9 is considered to be in general accord with the velocity models obtained through microseism analysis and seismic prospecting.

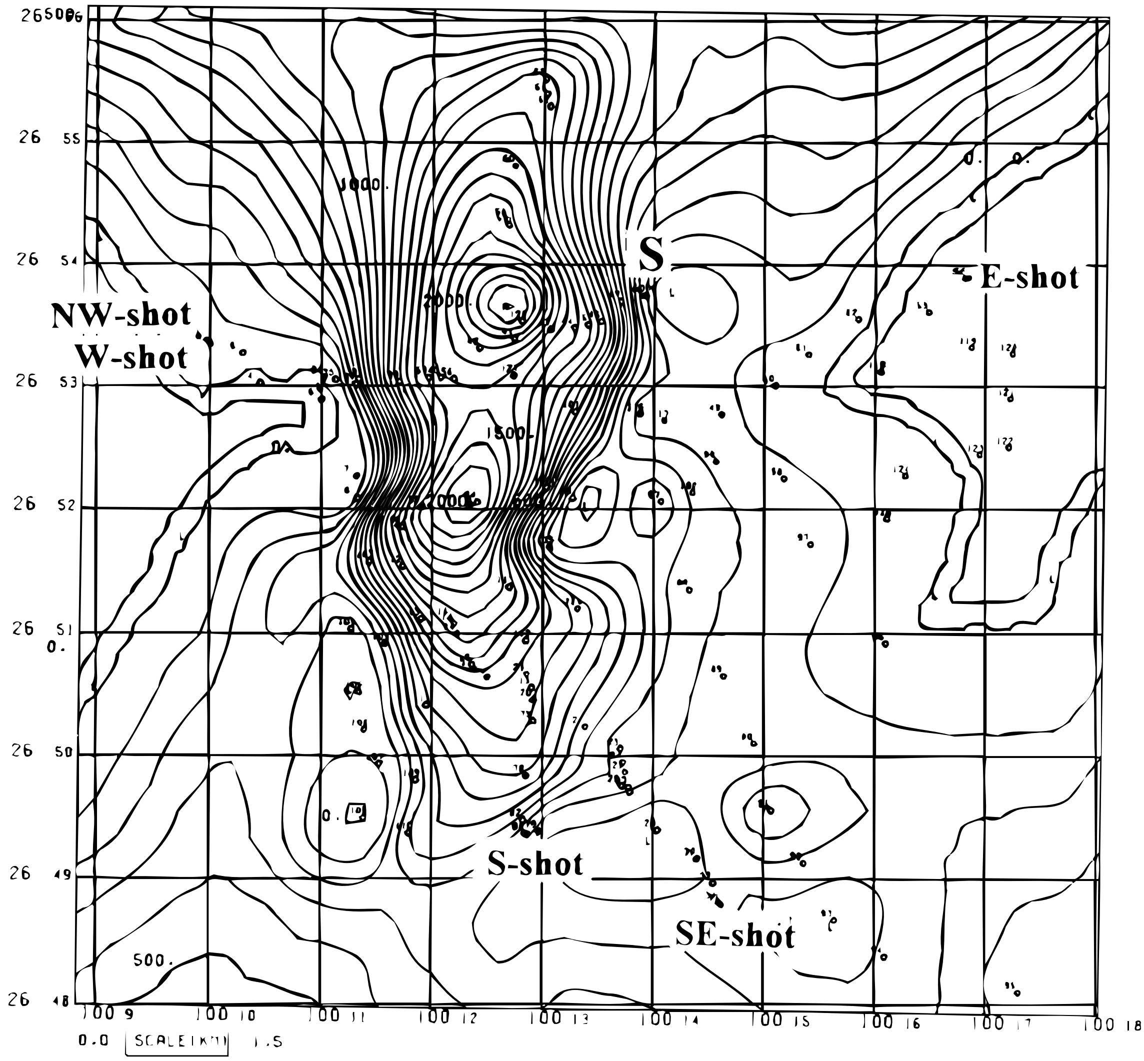


Figure 9 Distribution of depth to bedrock in the central and southern parts of Lijiang basin obtained from Bouguer gravity anomaly. Contour interval is 100 m.

5. DISCUSSION

The structural models obtained are preliminary because of poor constraints on the velocity distribution in the bedrock and the lack of gravity data on the surrounding mountain areas; there is a difference in the estimated depth to bedrock in the basin between the velocity and density structural models. However, both models suggest that, the bedrock subsides steeply along the west and east edges of the basin. The west bedrock subsidence is probably related to vertical displacement of bedrock across the Xueshan fault, which is considered to be the seismogenic fault of the 1996 Lijiang Earthquake. It is important to note that, the most severe earthquake damage in the basin was found not on the west edge but in the areas located about 1.5 km apart from the edge. This situation reminds us of the similar damage distribution in Kobe-Hanshin area caused by the 1995 Hyogoken-nanbu (Kobe) earthquake [Akamatsu et al., 1997b], showing that, the steep configuration of bedrock may bring the so-called basin-edge effect [Pitarka et al., 1997] and/or the focusing effect [Nakagawa et al., 1996].

On the other hand, no significant change in depth to bedrock was found across the Lijiang-Jianchuan fault, thereby implying that the displacement across the fault is mainly of strike-slip type. It is suggested out of this that, the spatial change in degree of damage on this fault zone should be attributed to reasons other than the configuration of bedrock. Fig. 10 shows the distribution of zones with the most severe damage in the Old Town on the northeastern part of the fault zone in the basin: the most severe damage

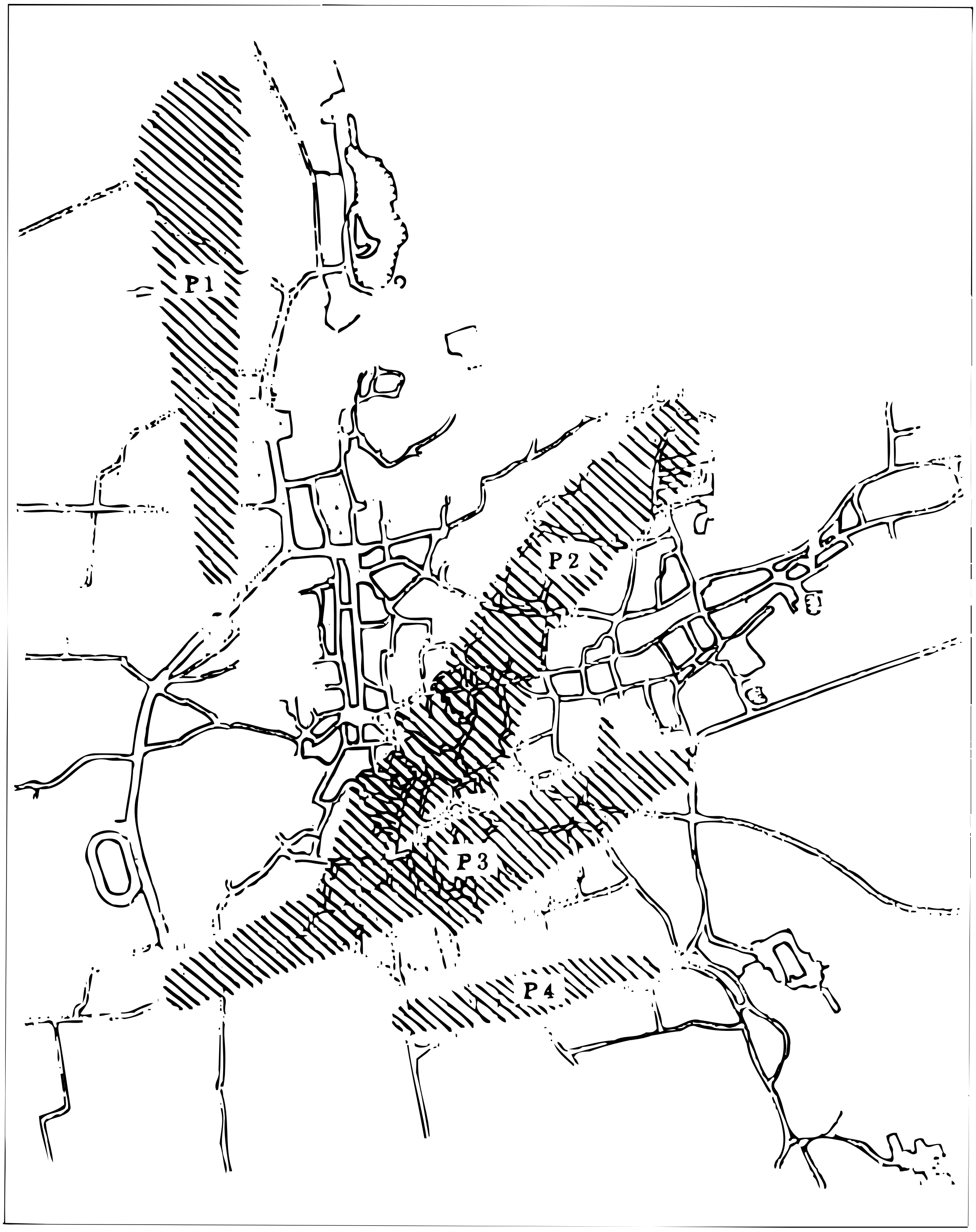


Figure 10 Distribution of severely damaged zones in Lijiang Old Town for the 1996 Lijiang Earthquake.

was observed in several narrow belt-like zones. Jiang [1997] found that, the predominant frequency of microtremors in these zones is lower than 3 Hz, while the frequency is higher than 10 Hz in the other areas with relatively low damage. In addition, a fault trending north-south direction is considered to be exist in the sediments of up to 60 m deep under the zone P1 in Fig. 10, on the basis of small-scale seismic experiments and underground radar survey carried out by Seismological Bureau of Yunnan Province [Jiang et al., 1999]. These observations suggest that, block boundaries characteristic of the fault zone are considered to have played an important role during the earthquake, and consequently brought the belt-like distribution of severe damage in the Old Town.

6. CONCLUSION

Anomalous distribution of damage to wooden houses and RC buildings was repeatedly observed in the Lijiang basin, during the 1996 Lijiang Earthquake and 1951 Jianchuang Earthquake: (1) the most severely damaged area was located in a belt-like zone 1.5 km far from the west basin edge and parallel with the Xueshan fault lying along the edge, and (2) remarkable change in degree of damage was found in the Lijiang-Jianchuan fault zone which crosses in the southern part of the basin in the NE-SW direction. To reveal the subsurface structure in the basin, mainly the fault-related bedrock configuration from the point of view of microzoning, array observation of microseisms, small-scale seismic refraction experiments, large-scale seismic prospecting across the basin, and gravity survey were carried out. Comparative analyses show that, bedrock subsides steeply at the west and east basin edges by more than 400 m, reaching up to 1,200 m or more deep in the central part. The steep subsidence at the west edge is considered to relate to the Xueshan fault of N-S strike. On the other hand, no significant change in the depth to bedrock was found across the Lijiang-Jianchuan fault zone, which implies that the fault is mainly the strike-slip type. In conclusion, the anomalous distribution of damage of (1) and (2) should be attributed respectively to the fault-related bedrock configuration with steep relief (basin-edge effect and/or focusing effect), and to the effects of block boundaries characteristic of the fault zone on seismic ground motions.

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