Seismicity in the Central Adirondacks with emphasis on the Goodnow, October 7, 1984 Epicentral Zone and its Geology

Lamont-Doherty Geological Observatory
of Columbia University
Palisades, New York 10964

Seismicity and deformation world wide are concentrated along plate boundaries, as the theory of plate tectonics predicts. Tectonic activity is also present in the interior of plates. No theory, however, can yet successfully predict the occurrence of this intraplate tectonism. One of the manifestations of intraplate tectonism is intraplate seismicity with the accompanying consequence of earthquake hazard. The potential damage from large earthquakes is of concern in the eastern U.S. because very large earthquakes are known from the pre-instrumental historic record. The concern stems not only from the potential destruction from a repeat of these events at the same location, but also from the possibility that similar earthquakes may occur elsewhere in the eastern U.S.

INTRODUCTION

Earthquake hazard in the eastern U.S. has been estimated by relying heavily on the assumption that the seismicity detected during historic time is representative of future occurrence. Recent studies, however, on the 1886 Charleston, S.C. earthquake raise doubts on the validity of this assumption. Some of the results make it possible, if not more likely, that future large damaging earthquakes may occur at locations other than the epicentral zones of the large historic earthquakes (e.g., Hayes and Gori, 1983). This uncertainty about one of the fundamental premises for earthquake hazard analysis is symptomatic of the poor understanding we have of intraplate seismicity and tectonics in general. Clearly, a reliable estimate of earthquake hazard in the eastern U.S. and in other intraplate regions, depends on an improved understanding of the tectonic processes active in these regions.

The earthquakes themselves are one of the most important sources of information on intraplate tectonics. During the past 15 years the Lamont-Doherty Geological Observatory of Columbia University as been monitoring seismicity in New York and surrounding states from a telemetered seismic network and from temporary networks deployed in aftershock zones. It has been clear from the beginning that a key to an improved understanding of intraplate neotectonics was to combine information on seismicity, crustal structure, and stress (e.g., Sbar and Sykes, 1973; Aggarwal and Sykes, 1978; Yang and Aggarwal, 1981). The fault movements manifested by the seismicity must be the consequence of a stress field acting on a geologic environment characterized by fault zones that would tend to distort the stress field and cause stress concentrations.

[1] also at Department of Geological Sciences, Columbia University

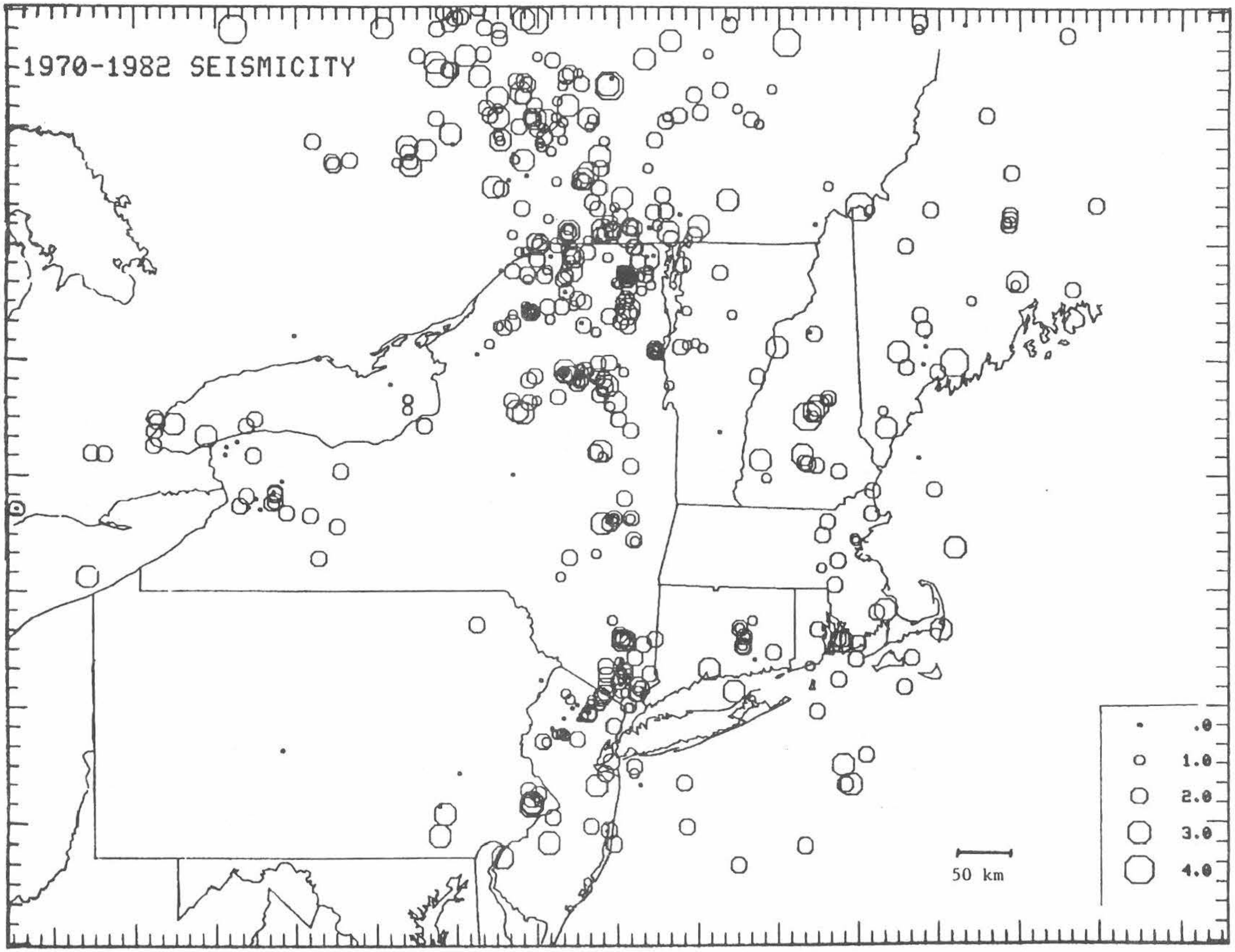

Figure 1. Twelve years of earthquake data from the New York-New Jersey Seismic Network.

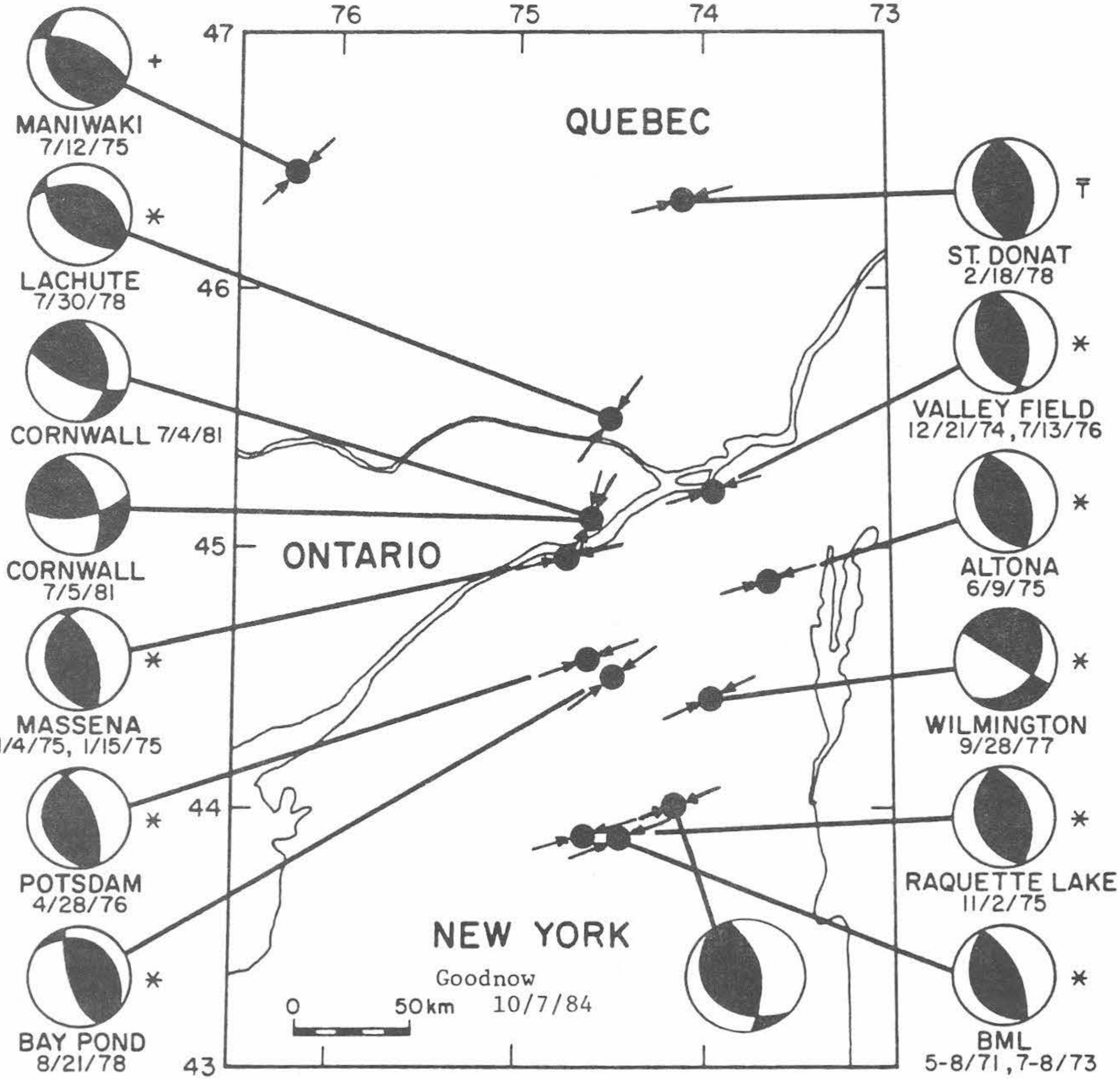

Figure 2. Fault-plane solutions from the Adirondack-Ontario seismic zone. Reverse faulting predominates and the P axes are predominantly ENE. The fault-plane solution of the Goodnow earthquake is shown at bottom center and fits this pattern.

The Goodnow, 7 October, 1983 magnitude 5.1 (M_S) earthquake in the Central Adirondacks offered a new opportunity to study an earthquake in one of the prominent areas of seismicity in the eastern U.S. (Seeber et. al. 1984; Suarez et. al., 1984; Figure 1). A previous earthquake of similar size in the same area occurred in the northern Adirondacks near Messina, N.Y. in 1944 (M_S=5.6). The study of the Goodnow earthquake has been directed at three main goals: 1) constraining the source parameters of the main shock primarily from body and surface waves recorded teleseismically; 2) resolving the characteristics of the aftershock sequence and other related seismicity from data of both the fixed stations of the telemetered network and from data of the portable network; and 3) understanding the relationship between seismicity and structural features that characterize the Grenville basement in the seismogenic zone. This last item will be the primary concern here.

MAIN SHOCK-AFTERSHOCK SEQUENCE

Main Shock-Focal Parameters

The characteristics of the Goodnow, 7 October 1983 main shock (Suarez, et al., 1984) are: moment is M_o = 2.5 x 10^{23} dyne cm (from long period Raleigh waves); source radius is r ≈ 0.5 to 1.2 km (from body wave modeling and assuming a circular rupture with a rupture velocity = 0.9 V_S); static stress drop is then $\Delta\sigma$ = 870 bars to 120 bars, respectively (assuming a Brune's model); the average fault displacement is w = 80 cm to 14 cm (assuming rigidity μ = 4 x 10^{11} dynes/cm^2); focal depth is h = 7.5 ± 0.5 km; rupture plane strikes N to N 15° west. The fault plane solution of the Goodnow main shock is well constrained and is consistent with an E to ENE P axis, in remarkable agreement with previous fault plane solutions in the Adirondacks (Figure 2).

Main Shock - Intensity

The intensity data from the Goodnow main shock are still being compiled. Near field data was collected locally shortly after the event. These data are scanty and non-uniformly distributed, reflecting the population distribution in this remote area. Nevertheless some interesting patterns emerge (Figure 3). An area of maximum intensity can be recognized within the valley containing Catlin Lake and the epicenter. Masonry structures tended to be slightly damaged (cracked walls and broken chimneys) and several landslides were reported in this area. These are indicators of Modified Mercalli intensity VII. At a distance somewhat less than the hypocentral depth of the mainshock (≈ 8 km) from the epicenter the intensity level drops off significantly. The 1944 Messina earthquake destroyed more than a thousand chimneys in that town. Considering that the majority of the chimneys in the Goodnow meizoseismal area were damaged, it is possible that considerable damage could have been caused by the Goodnow event, had it occurred beneath a large town.

Aftershock Distribution

Within 24 hours of the main shock a number of portable seismographs were established in the Goodnow epicentral area. A portable network

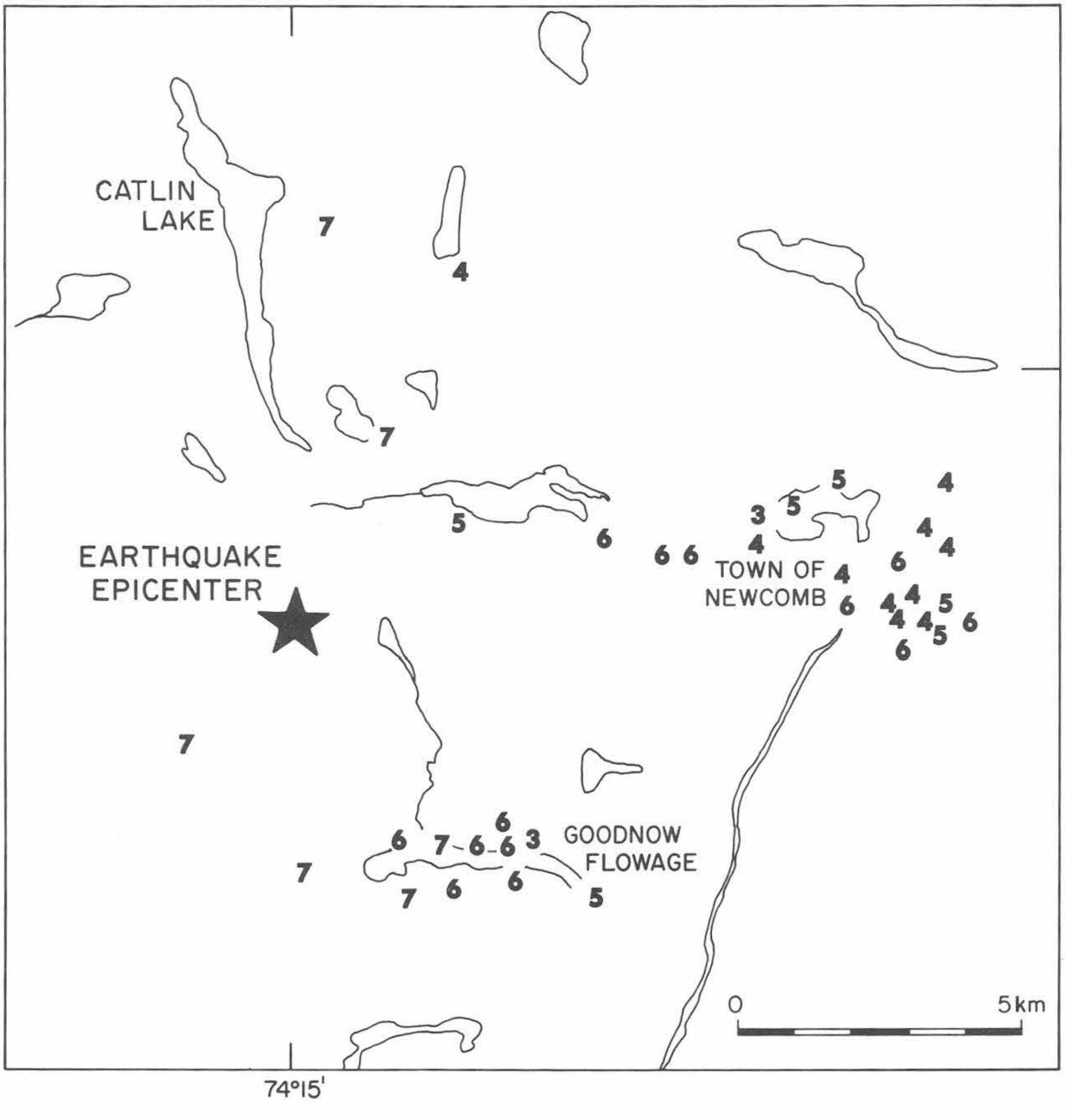

Figure 3. Epicentral intensity map of the Goodnow, Oct. 7, 1983 main shock. Numbers are Modified Mercalli intensities. Intensity VII reports are confined to a narrow zone elongated along the NNW trending Catlin Lake lineament. This orientation is parallel to the fault plane defined by the largest cluster of aftershocks and consistent with the steep, west-dipping nodal plane of the fault-plane solution for the main shock.

remained operative for 22 days after the main shock when three additional stations of the permanent network became operative (Figure 4). The data from this initial period yielded 93 accurate hypocenters (Figures 4-6) from which we can resolve 1) a planar clustering striking ≈ N 15° west and dipping 60° west, an orientation close to that of one of the planes in the fault plane solution of the main shock; 2) the geometry of this clustering, which appears to be annular when viewed normal to this plane with hypocenters concentrated at the border of a circle with a radius r ≈ 0.75 km, in excellent agreement with constraints on the rupture of the main shock (Figure 7); 3) first motion data from the aftershocks, most of which are consistent with the fault plane solution of the main shock; 4) very few aftershocks outside of this annular cluster. The aftershock zone grows slightly in time, but only away from the rupture plane, not along this plane. About 10 days after the main shock activity seems to gradually migrate over four days about 1 km up and to the west, off the inferred rupture plane, possibly along a complimentary fault (Figure 8), which would dip shallowly eastward and nearly coincide with the downward extrapolation of the Blue Mtn. Lake fault active in the 1971-73 swarms (e.g., Yang and Aggarwal, 1981; Figure 9).

SEISMICITY AND GEOLOGY

Seismicity and Brittle Structures

The Adirondack massif is characterized by prominent sets of linear topographic features. The most prominent set strikes NNE and includes long linear valleys such as the Long Lake valley and the upper Hudson valley (Figure 4). Some of these appear to be fault controlled (Isachsen and McKendree, 1977). Another set of linears strikes WNW, this set includes the Raquette Lake lineament which has been tentatively associated with the seismogenic fault responsible for the 1975 sequence in that area (Yang and Aggarwal, 1981). Another linear in this set recognized by Isachsen and McKendree (1977) is the Catlin Lake lineament (Figure 4). This lineament is close to the surface extrapolation of the inferred rupture plane and may be controlled by the same steeply dipping fault. No prominent linear feature seems to be associated with the shallow-dipping Blue Mt. Lake fault (Yang and Aggarwal, 1981).

Plumb and others (1984) measured strain relaxation, rock anisotropy data, and conducted borehole fracturing experiments in this region to assess *in situ* stress. The various techniques gave internally consistent results. Bearings of maximum strain relaxation (ε_1) are generally aligned with topographic contours and often the mechanically stiff direction of borehole cores. Furthermore, ε_1 is aligned with the inferred ENE regional stress, local p-axes, Precambrian structures, and local joints. They hypothesized that this alignment of ε_1 with other structures is the result of a feedback between tectonic stress and the process of jointing during the development of local topography.

We are currently investigating brittle features in the Goodnow epicentral area (Figure 10). This work is at a very preliminary stage. We have found evidence of brittle faulting along the EW contact zone between the Quartzo-feldspatic basal gneiss in the Goodnow Mt. area and

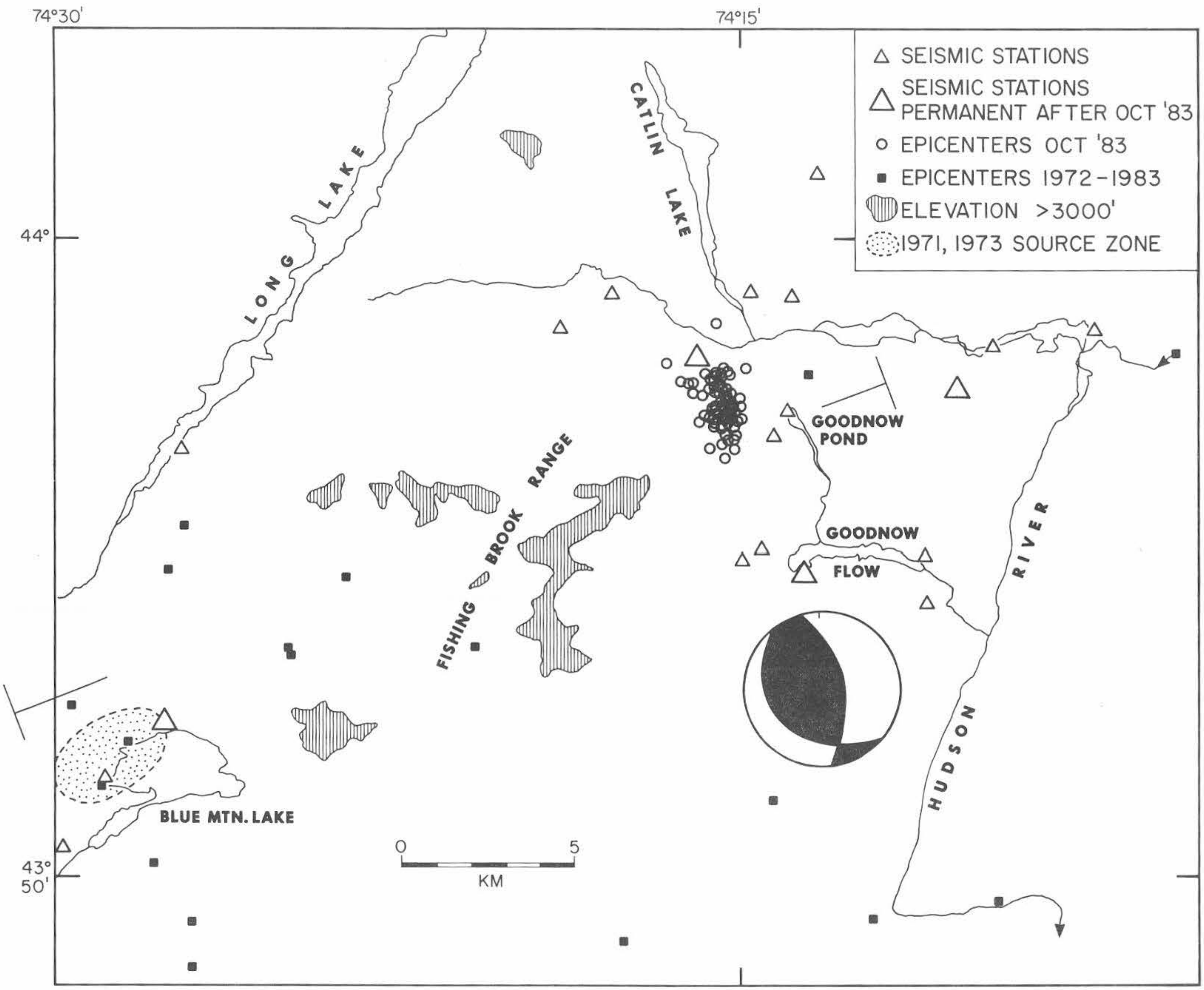

Figure 4. Blue Mt. Lake-Goodnow area of the central Adirondacks. Seismicity from 1972-83 (squares) is located by the regional seismic network and from Oct. 7-29, 1983 (circles) is located by the network of temporary stations (triangles; L-DGO and USGS). The area of the 1971 and 1973 Blue Mt. Lake swarms is also indicated (shaded). Large triangles are stations of the permanent network after Nov. 1, 1983. Catlin Lake and Long Lake are part of linear topographic features possibly associated with brittle faults (Isachsen and McKendree, 1977).

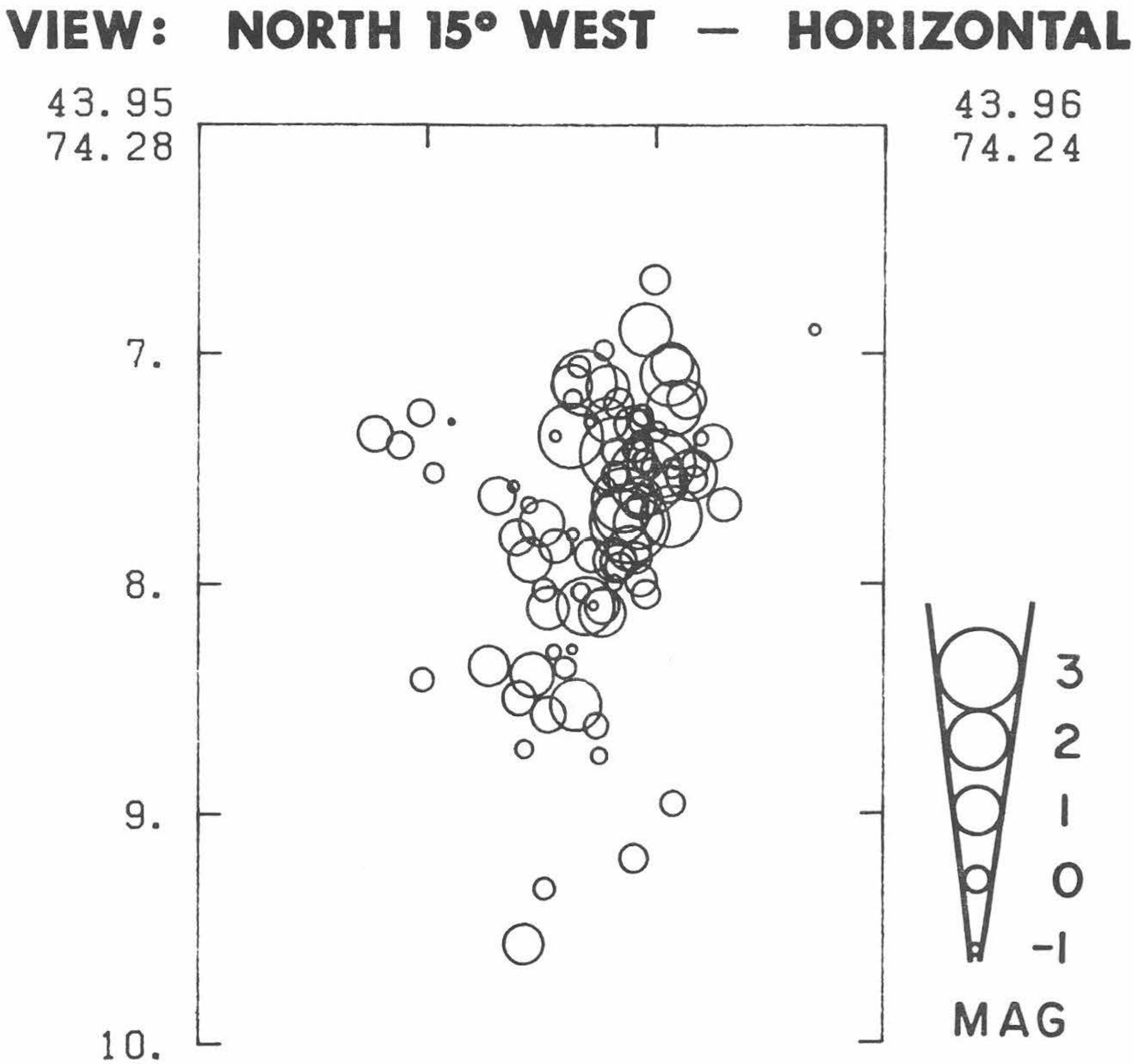

Figure 5a. North 15° west view of the Goodnow aftershocks. This section was chosen among many other sections with strikes differing from this by as litle as 5°, to yield the narrowest scatter in hypocenters about a plane, presumably the plane of the main rupture. Thus, the hypocenter data agree well with the first-motion data and indicate that the NNW-striking plane dipping steeply to the west in the fault-plane solution is the main rupture plane.

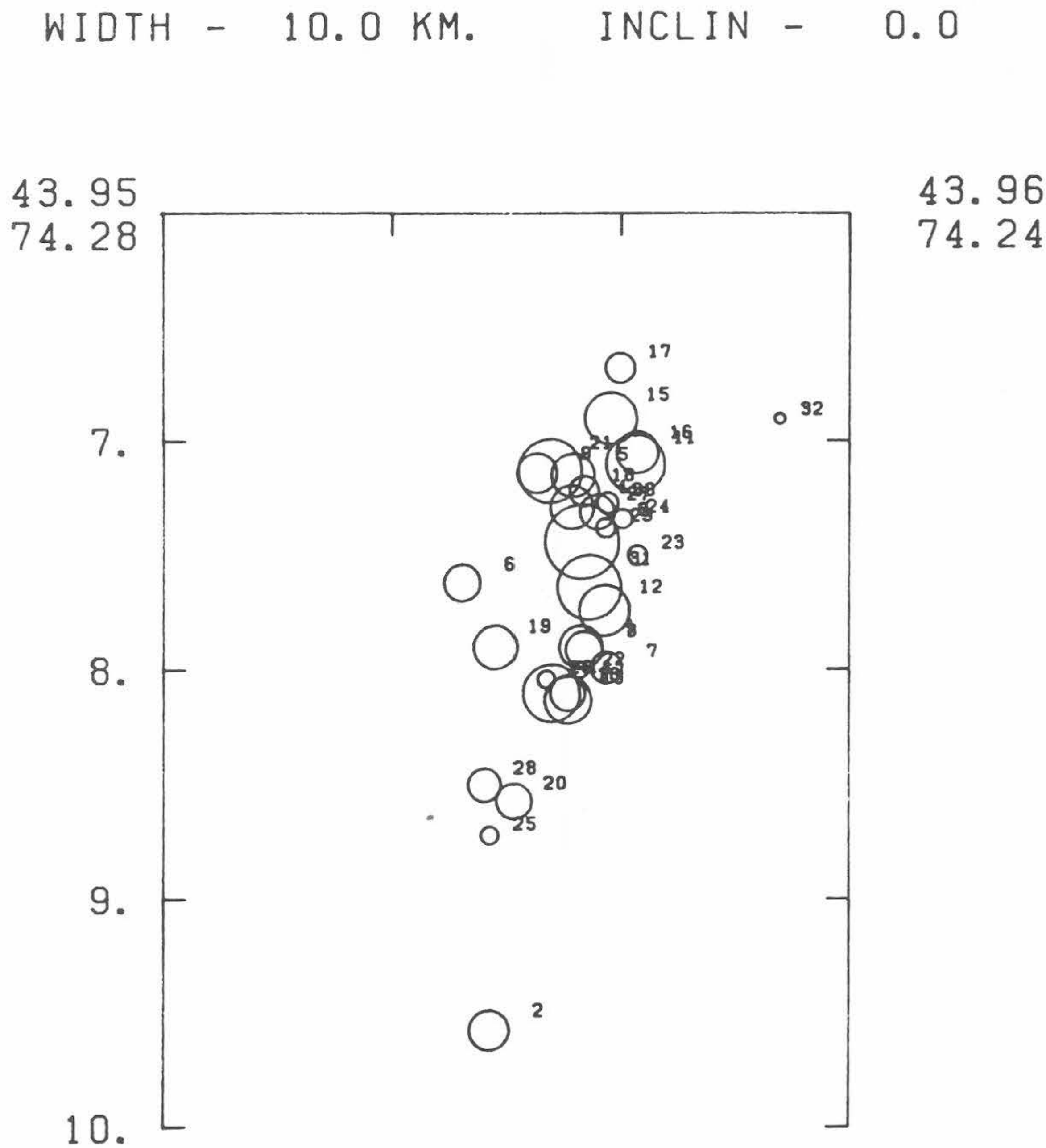

Figure 5b. First 32 aftershocks (recorded during first 5 days). Note how distribution is more planar than in **Figure 5a** and defines the rupture zone despite lower quality of locations than for later aftershocks. Thus scatter in Figure 5a is probably real.

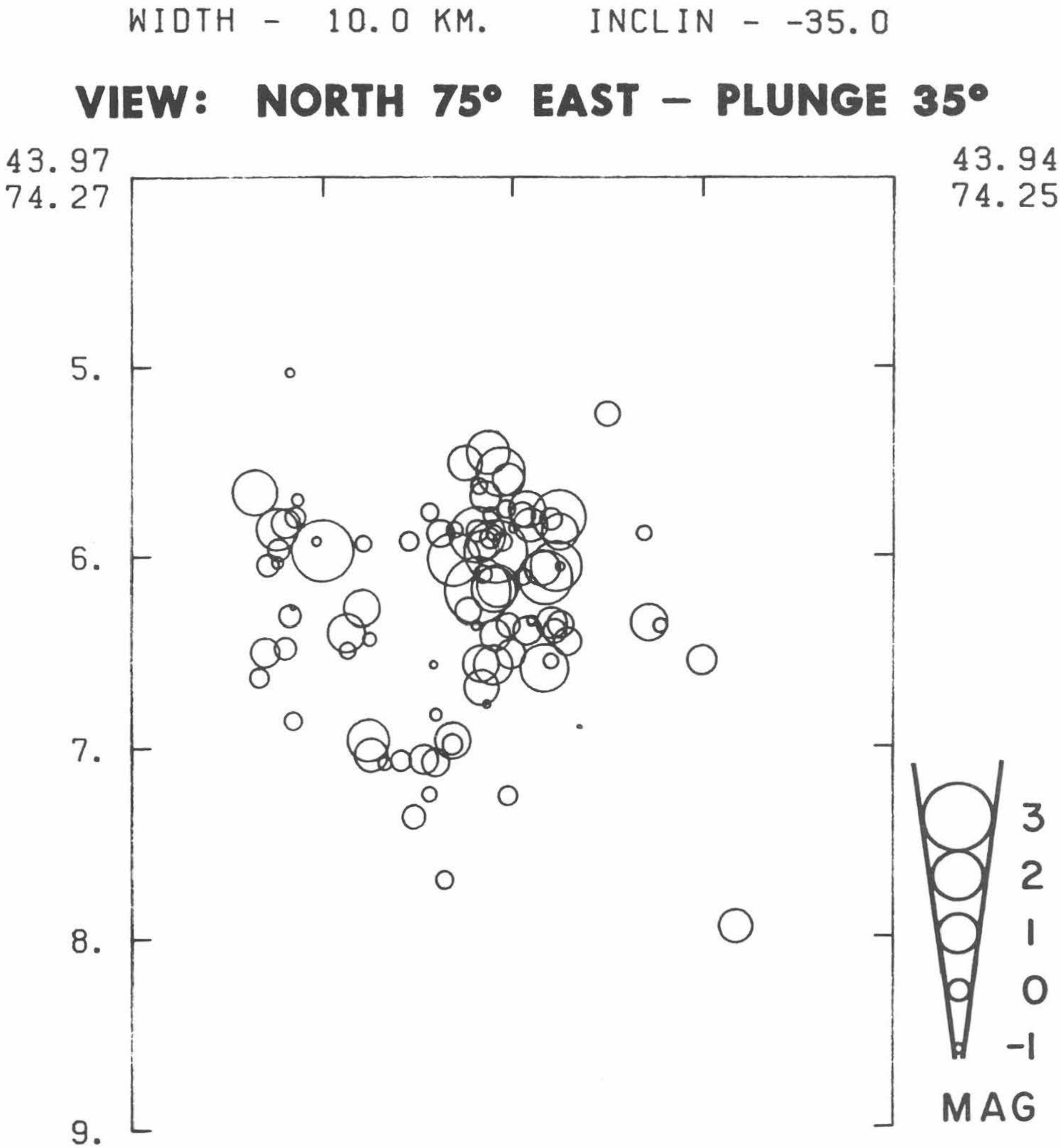

Figure 6. The Goodnow aftershock zone viewed perpendicular to the inferred plane of the main rupture (i.e., viewed north 75° east at a plunge of 35°; note that the plane of this section is not vertical and the numbers do not reflect true depth).

From the data in this figure we estimate the main rupture to be about 1.5 km in diameter and extend from about 7 to 8½ km depth.

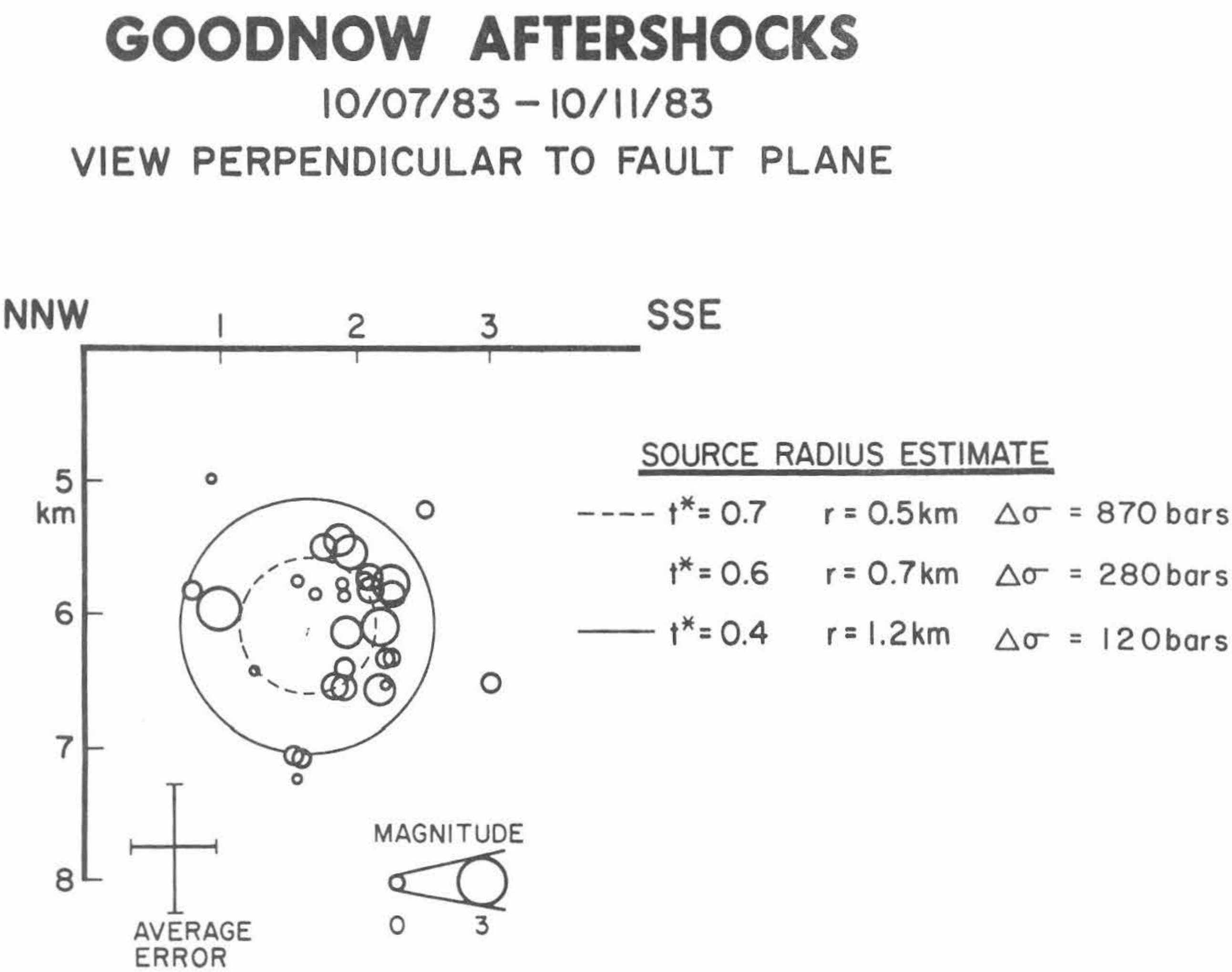

Figure 7. The first 29 well recorded aftershocks of the Goodnow earthquake viewed perpendicular to the inferred fault plane. The circles give the range in rupture dimension inferred from modeling the short period teleseismic P waves, assuming $Mo = 2.5 \times 10^{23}$ dyne-cm (obtained from long period Raleigh waves), a velocity of rupture = 0.9 Vs, and rupture nucleation at the center; t* is an attenuation parameter. The circles are centered at the hypocentral depth inferred from the moment tensor inversion. These data indicate that the aftershocks are confined for the most part to the rupture or near its outer edge where stress is expected to be concentrated (from Suarez, et al., in preparation).

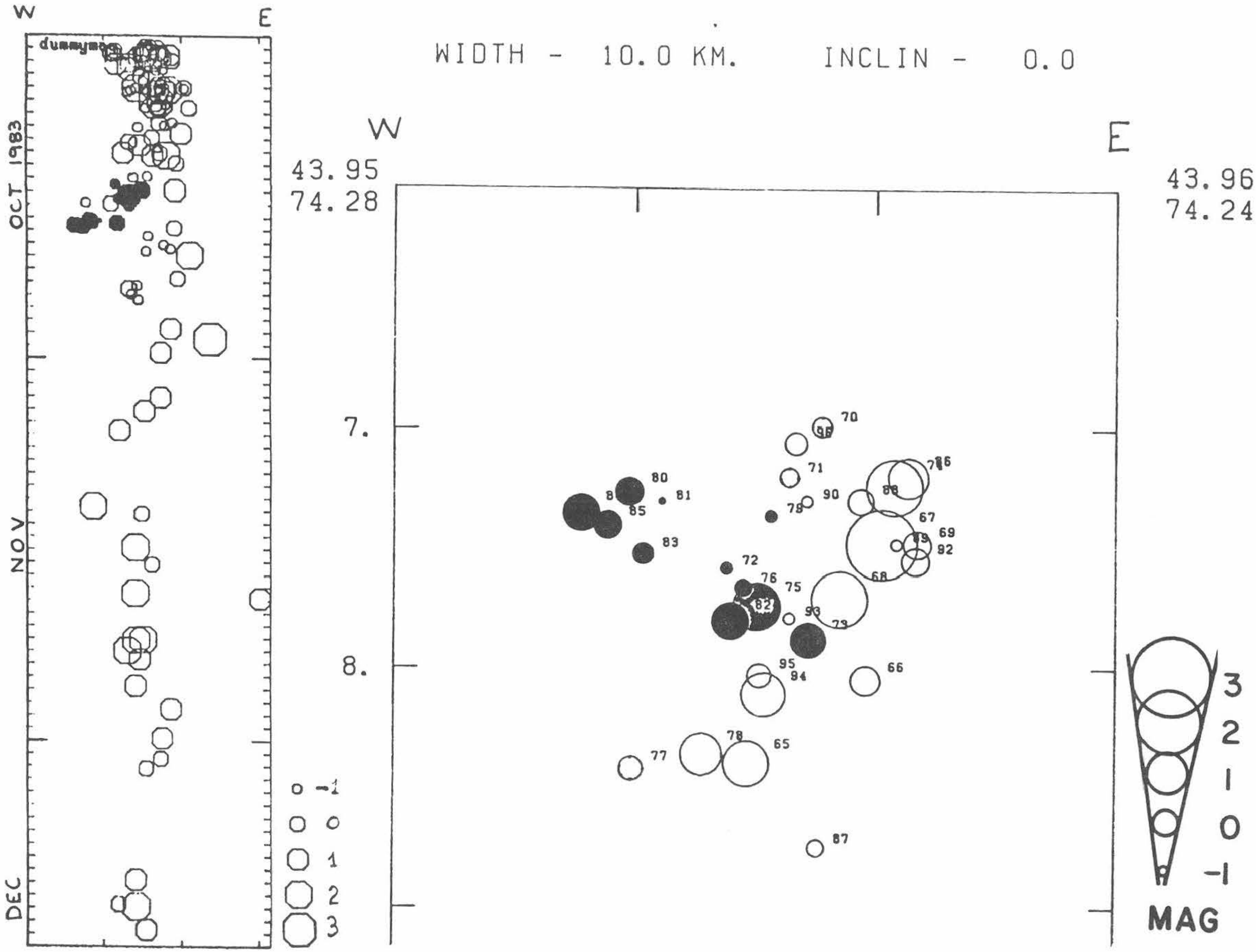

Figure 8. Time-space data suggesting the propagation of slip along a conjugate fault away from the main rupture. On the left is a time-space plot of the Goodnow epicenters projected on the line of the section in on the right (view along main upture as in Fig. 5). Most of the earthquakes in a tight westward migrating sequence occur on a plane dipping eastward and extending about 1 km from the main rupture (blackened symbols). This migration seems to take about 4 days.

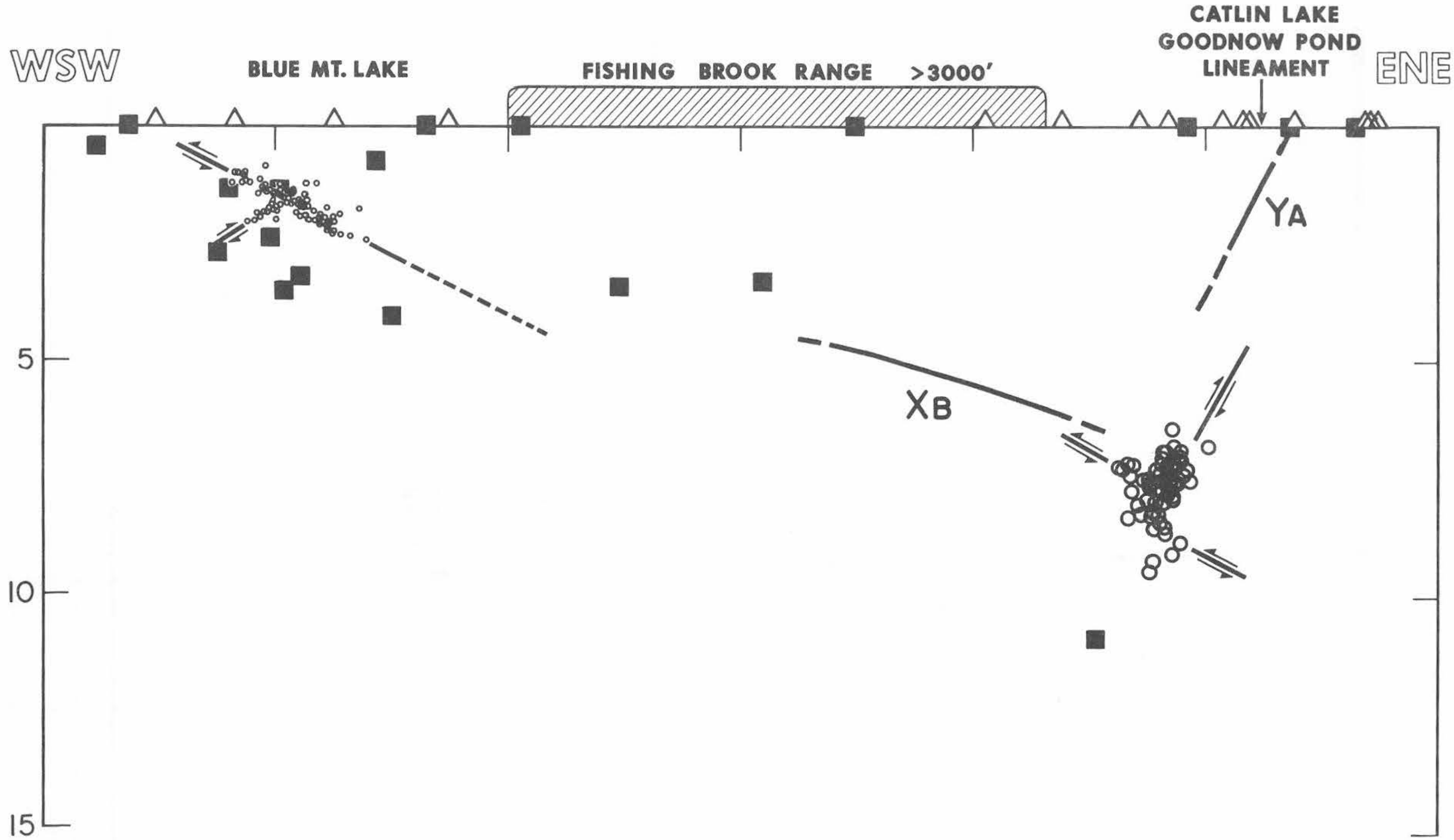

Figure 9. Section through the Goodnow and Blue Mt. Lake area (located in Fig. 4; no vertical exaggeration). Seismicity in Fig. 2 ± 20 km from plane of section is included (same symbols). Hypocenters for the 1971-73 Blue Mt. Lake swarms are from Yang and Aggarwal, 1981. Active faults delineated by spatial and temporal distribution of hypocenters and by first-motion data are indicated. Depth control for events located only by the regional network is generally poor. It is possible that seismicity after the Blue Mt. Lake swarms and before the Goodnow event (squares) was on the same system of faults active during the well-located sequences in 1971, 1983, and 1983. X_b and Y_a are possible reflectors identified on COCORP reflection data (Klemperer et al., 1984).

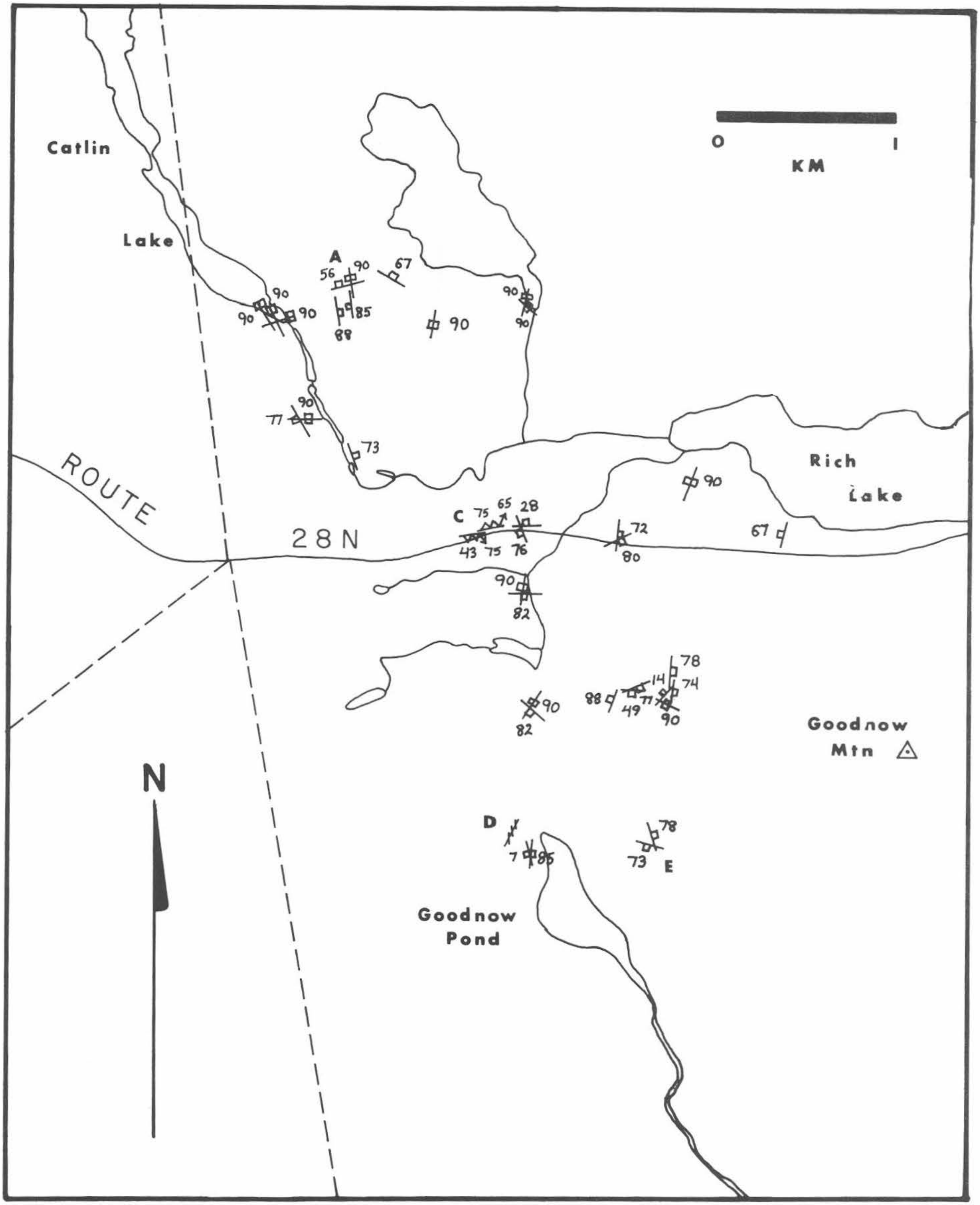

Figure 10. Joint and slickenside measurements made during a reconnaissance of the Goodnow epicentral area. Strike symbols with boxes denote joint planes; strike symbols with double barbs denote slickenside planes with rake of slickensides in plane given by arrow. Note that NNW trending joints give way to NNE trending joints to the east of the Catlin Lake-Goodnow Pond lineament. Data was mapped onto 1:25,000 scale air photos. **A.** Outcrop with N trending joint having aligned quartz crystal growth; **C.** Slickensided outcrop along Route 28N; **D.** Set of en echelon cracks; individual cracks trend 011°, crack train trends 027° (right-stepping offset); **E.** Joint oriented 163,78E contains possible gouge. Dashed lines are town boundaries.

the metasediments of the Grenville (series) to the north (McLelland and Isachsen, 1980). No evidence of faulting has yet been found along the Catlin Lake lineament, but this lineament appears to be joint controlled. The dominant joint set tends to strike NNE, parallel to the Long Lake lineament set, except in the vicinity of Catlin Lake where it strikes NNW.

Seismicity and Grenville Ductile Structure

A map of seismicity in the Adirondacks detected by the New York State seismic network during the last 10 years shows clustering of epicenters in well defined zones separated by aseismic zones (Figure 1). Two prominent zones strike approximately ENE and form broad arcs concave to the south in the western half of the Adirondack massif. When superimposed on structural (Figure 11) or lithologic (Figure 12) maps, these seismic zones appear to follow structural trends of Grenvillian age. This correlation between structure and seismicity cannot be interpreted as simple reactivation since the seismogenic faults appear to strike consistently NNW (Figure 2), at a large angle to the structural trends and seismic zones. The Goodnow earthquake is at the intersection between the ENE striking Central Adirondack seismic zone and another seismic zone striking NNW, parallel to the inferred plane of faulting, that can be traced southward to near the southern edge of the Adirondack massif.

McLelland and Isachsen (1980) have proposed a south verging Wakely Mt. nappe cored with the basal quartzo-feldspatic gneiss and covering most of the southern Adirondacks (Figure 12). The root zone of the Wakely nappe would closely follow the central Adirondack seismic zone. It is likely that a major structural boundary is associated with the central Adirondack seismic zone because 1) foliation data forms a band of subparallel and gently curving trends along this zone (Figure 11), in contrast to the adjacent aseismic regions where the foliation trends are relatively convoluted; and 2) the western half of this seismic zone corresponds to the boundary between areas of foliation that dip consistently southward to the north and northward to the south (Figure 11).

In summary, available earthquake and geologic data in the Adirondacks suggest that Grenville age structure is controlling some aspects of the seismicity. This result is in agreement with Plumb et al. (1984). This control cannot, however, be simple reactivation of Grenville structures, since seismogenic faults are at large angles to these structures. We are considering the possibility that seismicity is lithologically controlled. In this case, the relation between structure and seismicity would be a consequence of the control that structure has on lithology. The Adirondacks provide one of the best opportunities to carry out a detailed comparison between geology and seismicity because the seismogenic part of the crust is exposed and can be studied, and seismicity is relatively high and well monitored. Our current field investigation in the Goodnow - Blue Mt. Lake area of the central Adirondacks is directed at improving constraints on Grenville structures so that a reliable structural model can be developed and compared with the seismicity.

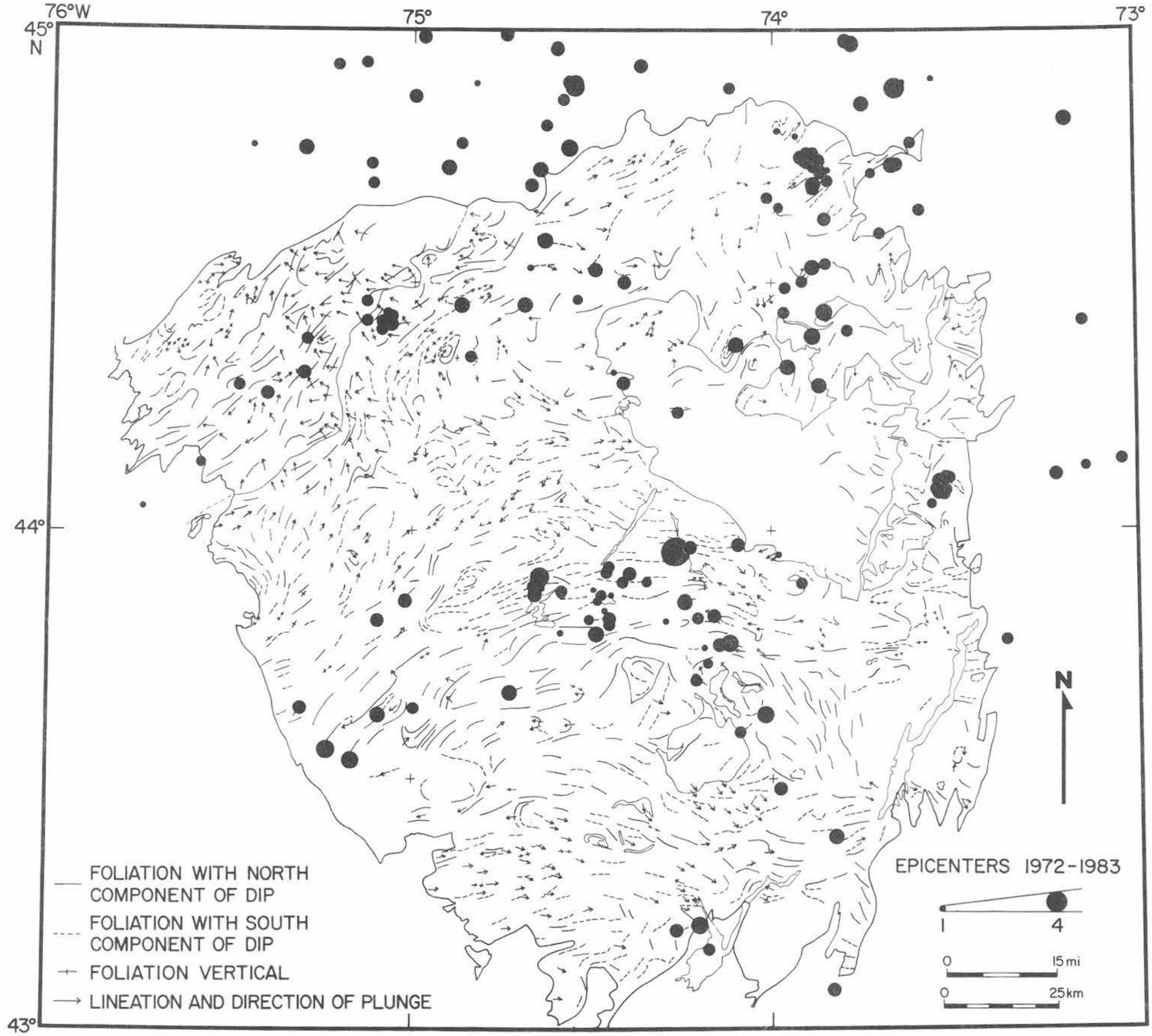

Figure 11. Epicenters from the N.Y. State Seismic Network, 1972-1983 (black dots) superimposed on foliation and lineation data extracted from the 1:250,000 N.Y. State geologic map (Fisher et al., 1970). Two arcuate belts of seismicity in the central and northwestern Adirondacks are clearly related to Precambrian (Grenville) structural trends. Large domains where dips of foliation have either a north or south component can be recognized. The portion of the east-west seismic belt in the central Adirondacks which contains the Raquette Lake, Blue Mt. Lake, and Goodnow earthquakes is closely associated with the boundary between two zones with southerly and northerly dip of foliation, respectively.

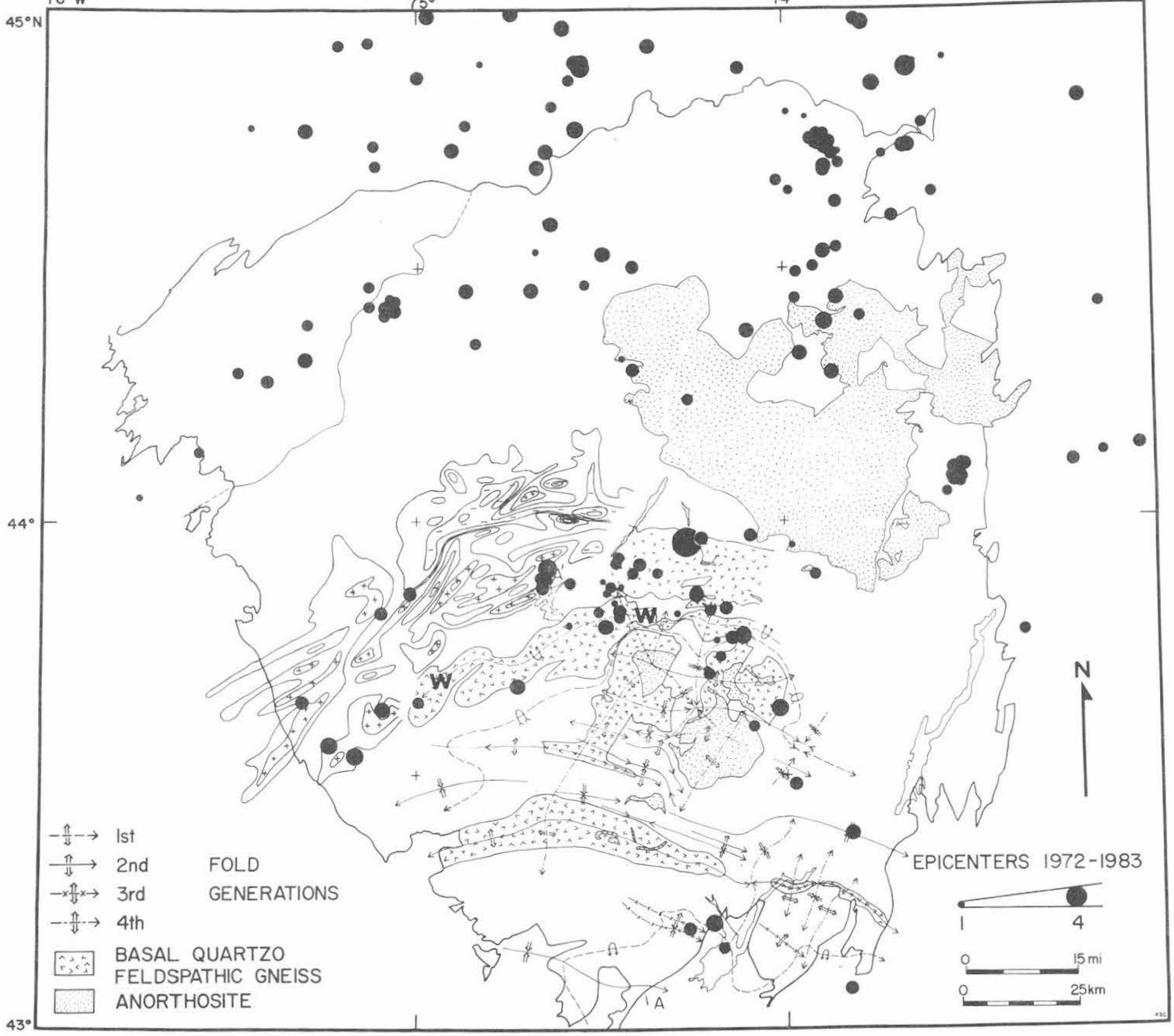

Figure 12. Epicenters from the N.Y. State Seismic Network, 1973-1983 (black dots) superimposed on a structural/lithologic map of the southern and central Adirondacks modified from McLelland and Isachsen (1980) and of magnetic data (Zietz and Gilbert, 1981) beyond the limit of McLelland and Isachsen's map (areas with '+' have magnetic intensity − 1200 gammas; areas with '−' magnetic intensity − 600 gammas). The quartzofeldspatic gneiss differentiated in this map is thought to be the basal stratigraphic unit and is tentatively interpreted as a pre-Grenville basement. Four phases of Grenville deformation have been identified from these data. W indicates trace of Wakely Mtn. nappe root zone. Note remarkable correlation between epicentral zones and arcuate Grenvillian structural trends in the central and northeastern Adirondacks.

FIELD TRIP STOPS

While field trip stops are not yet final at time of writing, likely stops include outcrops A, C, D, and E in Figure 10 and some of the Intensity VII effects (Figure 3).

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REFERENCES

Aggarwal, Y.P. and Sykes, L.R., 1978, Earthquakes, faults, and nuclear power plants in southern New York and northern New Jersey, Science, 200, 425-429.

Fisher, D.W., Isachsen, Y.W., Rickard, L.V., 1970, Geologic map of New York (scale 1:250,000), N.Y. State Museum and Science Service Map and Chart Series 15.

Hayes, W.W. and Gori, P.L., eds., 1983, A workshop on "The 1886 Charleston, South Carolina, earthquake and its implications for today", U.S. Geol. Surv. Open File Rept. 83-843, 508 p.

Isachsen, Y.W. and Mckendree, W.G., 1977, Preliminary brittle structure map of New York (Scale 1:250,000), N.Y. State Museum Map and Chart Series 31A.

McLelland, J. and Isachsen, Y., 1980, Structural synthesis of the southern and central Adirondacks: A model for the Adirondacks as a whole and plate-tectonics interpretations: G.S.A. Bulletin, Part II, 91, 208-292.

Klemperer, S.L.,Brown, L.D., Oliver, J.E., Ando, C.J., Czuchra, B.L. and Kaufman, S., 1984, Some results of COCORP reflection profiling the Grenville-age Adirondack Mtns., New York State, preprint.

Plumb, R., Engelder, T., and Sbar, M., 1984, The comparison between stress directions in outcrops and those inferred from earthquakes near Blue Mtn. Lake, New York, J. Geophys. Res., in press.

Sbar, M.L. and Sykes, L.R., 1973, Contemporary compressive stress and seismicity in eastern North America, an example of intraplate tectonics, Geol. Soc. Am. Bull., 84, 1861-1881.

Seeber, L., Barstow, N., Cranswick, E., Armbruster, J.G., Suarez, G., Coles, K. and Aviles, C., 1984, Grenville structure and the Central Adirondack seismic zone including the October 7, 1983 main shock - aftershock sequence, Joint Programme with Abstracts, Canadian Geophysical Union, 11th Annual Mtng., Halifax, 29 May - 1 June, 1984, 66.

Suarez, G., Seeber, L., Aviles, C. and Schlesinger-Miller, E., 1984., The Goodnow, N.Y. earthquake: Results of a broadband teleseismic analysis, EOS, Am. Geophys. Union Trans., 65, 239-240.

Yang, J.P. and Aggarwal, Y.P., 1981, Seismotectonics of northeastern United States and adjacent Canada, J. Geophys. Res., 86, 4981-4998.

Zietz, I. and Gilbert, F.P., 1981, Aeromagnetic map of New York (Scale 1:250,000), U.S. Geol. Surv. Geophys. Investigations Map 938.