applying the existing [illegible] known as Appendix A, "Seismic and Geologic Siting Criteria for Nuclear Power Plants" (7), to sites in the East.

Reports

Earthquakes, Faults, and Nuclear Power Plants in Southern New York and Northern New Jersey

Abstract. *Seismic activity in the greater New York City area is concentrated along several northeast-trending faults of which the Ramapo fault appears to be the most active. Three nuclear power plants at Indian Point, New York, are situated close to the Ramapo fault. For a reactor site in use for 40 years, the probability that the site will experience an intensity equal to or in excess of the design (safe shutdown) earthquake is estimated to be about 5 to 11 percent.*

The Ramapo fault system, which bounds the Triassic-Jurassic Newark graben on its northwest side, has been known for about 100 years but has been commonly presumed to be an inactive fault. Prior to the advent of plate tectonic concepts in the late 1960's, Triassic deformation was generally thought to be "the last dying gasp of Paleozoic orogeny." The separation of North America from Africa in the Triassic-Jurassic is now generally recognized as the last great tectonic event in the area, which greatly influenced the subsequent geologic history. The hypothesis that the fault is dead now appears to have been tenable only in the near absence of local instrumental earthquake data. Although a number of workers since 1964 (1) have suggested correlation of earthquakes with this and other nearby faults, the data were insufficient to definitely establish such correlations. The recent improvement in the seismographic coverage for this area enabled us to determine precise locations for 33 earthquakes and many focal mechanism solutions. The results clearly indicate that seismic activity is related to faults that trend northeast to north-northeast.

More people live within 80 km of the Indian Point reactors than within the same distance from any other nuclear power plant in the United States. The reactors are situated within 1 km of a major branch of the Ramapo fault system. As late as 1972, however, the Final Environmental Statement (2) for Indian Point reactor unit 2 stated, "There are no truly major faults in or near the site." This view was disputed by the State of New York, and that concern led to hearings on seismic safety held before the Atomic Safety and Licensing Appeal Board (ASLAB) of the Nuclear Regulatory Commission (NRC) in 1976 and 1977. In 1975 Ratcliffe (3) recognized an individual fault, possibly of the Ramapo system, that passes beneath reactor unit 3. Since then, considerable effort has been devoted to geologic mapping and studies of local earthquakes near the reactors (2, 4-6). Since late 1976, several shocks have occurred on the Ramapo fault both to the southwest and northeast of the plant as well as almost directly beneath it.

Scientific information and judgment are intimately involved in several of the questions litigated in the NRC hearings on Indian Point. Since we participated as

Figure 1 shows earthquakes in the northeastern United States and adjacent parts of Canada from 1970 to 1977 as detected by networks in the area. Since 1970 the number of seismic stations in this region has steadily increased. For the period covered in Fig. 1 the station coverage is more complete for New York State and adjacent areas and poorer for New England. For New York and adjacent areas the detection is probably complete for events larger than magnitude (m_b) 2. Since 1974 the detection is complete for $m_b > 1.8$ for the area near the Ramapo fault. We determined the magnitudes (m_b) of these and other events used in this report, using Nuttli's scale (8).

The overall spatial distribution of these events is remarkably similar to that of historical events for the period 1534 through 1959 (9). Both the record in Fig. 1 and the historic shocks show concentrations of seismic activity in the northern, western, and southeastern parts of New York State; the central part of the state is essentially aseismic.

Earthquake locations, faults, and focal mechanism solutions for southeastern New York and northern New Jersey are shown in Fig. 2. A more detailed description of the seismic data is given else

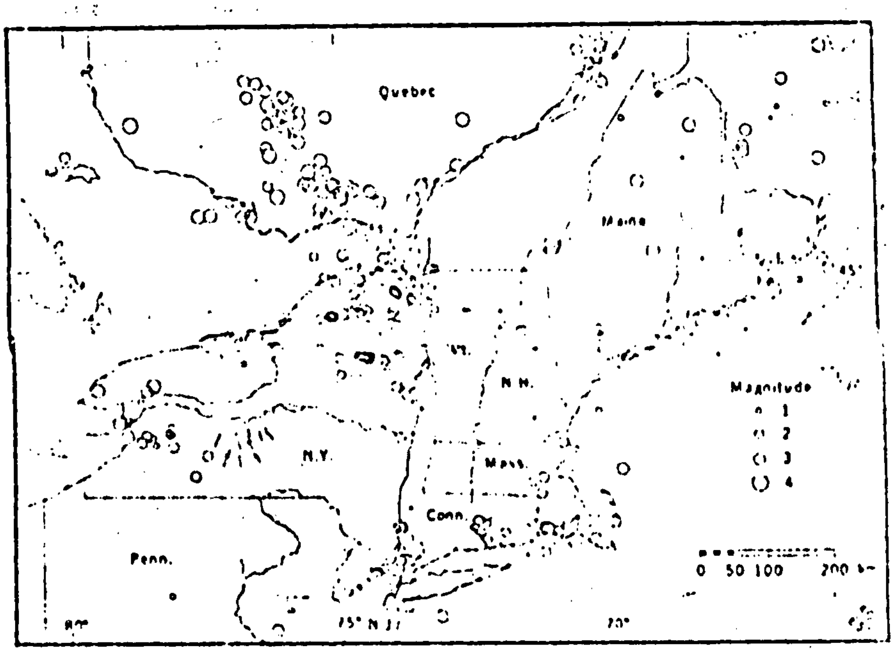

Fig. 1. Epicenters of earthquakes (1970 through 1977) in northeastern North America located by various networks in the area. Note the northeast alignment of earthquakes in northern New Jersey and southern New York. Stars denote events of unknown origin.

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where (6, 10). Figure 2 shows events ($1.0 \leq m_b \leq 3.3$) for the period 1962 to 1977 located with an accuracy of 5 km or better. Instrumental data for events prior to 1962 were generally found to be insufficient to allow us to meaningfully investigate their possible correlation with faults.

Figure 2 shows a strong spatial correlation of epicentral locations with surface traces of faults in this area. A large majority of the events lie on or very close (within 1 to 2 km) to the faults. Furthermore, an examination of the focal mechanism solutions shows that for each solution one of the nodal planes trends north to northeast, which is also the predominant trend of the faults in this area. This remarkable spatial correlation and the consistency of the nodal planes with the trend of the mapped faults leave little doubt that earthquakes in this area occur along preexisting faults.

About half of the events plotted in Fig. 2 are almost colinear and lie along or close to the Ramapo fault system. The Ramapo fault system can be traced as a single continuous fault between point A and event 26; near event 26 it splays into a number of branches (5, 11). One of these branches (the Thiells fault) passes within 1 km of Indian Point (triangle in Fig. 2). The association of seismic activity with this major fault system is particularly clear in Fig. 3, where the hypocenters of events with reliable focal depths occurring within 10 km of the fault trace are projected onto a vertical cross section perpendicular to the trend of the fault. The southeasterly dip of the hypocenters in Fig. 3 agrees with the dip of the faults determined from focal mechanisms and geologic evidence (4, 5).

Relatively little activity is found within the Triassic Newark basin, the area between the Ramapo fault and the Hudson River (Fig. 2). Similarly, very little ity (Figs. 1 and 2) is found to the no west of the line connecting events 4, 7. Some activity is found to the south of the Ramapo fault in the area ea the Hudson River. Hence, most of activity in Fig. 2 is located within bounding the Precambrian Hudson H lands.

The Ramapo fault system has exp enced at least four periods of move from Precambrian to Jurassic time (. Although Triassic-Jurassic movem has not been demonstrated along Ramapo fault on the east side of Hudson River, seismic activity is nea continuous along the entire zone. A Figure 3 indicates that seismic slip on Ramapo fault extends to a depth of ab 10 km. In contrast, much of the sei activity northwest of the Ramapo fa occurs at shallow depths (1 to 2 km) is of swarm type. This evidence sup that the Ramapo fault may have a gre seismic potential than adjacent f northwest of it.

Focal mechanism solutions indi that high-angle reverse faulting is predominant mode of contemp fault movement in this area; this dif from the sense of movement during Triassic-Jurassic (4, 5, 11). Thus state of stress in this area has cha with time. The present maximum pressive stress direction is nearly form and trends west-northwest and dicates reactivation of southeast northwest-dipping faults.

In a plate tectonic framework, the coast of North America was lo along a plate boundary during the assic but is presently a region interi a lithospheric plate. In a world study of intraplate phenomena, Sy (12) found that intraplate earthqu such as those in eastern North Ame tend to occur along major preexis faults that were reactivated by conti tal fragmentation in the Mesozoic or nozoic eras. Many of these reacti faults are still seismically active t but, of course, not to the extent that t were during the initial stages of conti tal rifting.

On the basis of focal mechanism tions, Aggarwal (10) postulated that activity in the New York City area belong to a larger seismotectonic p ince extending southwesterly to Vir approximately along the Fall Line. taceous and Cenozoic deformation found along that zone in Delaw Maryland, and Virginia (13). The

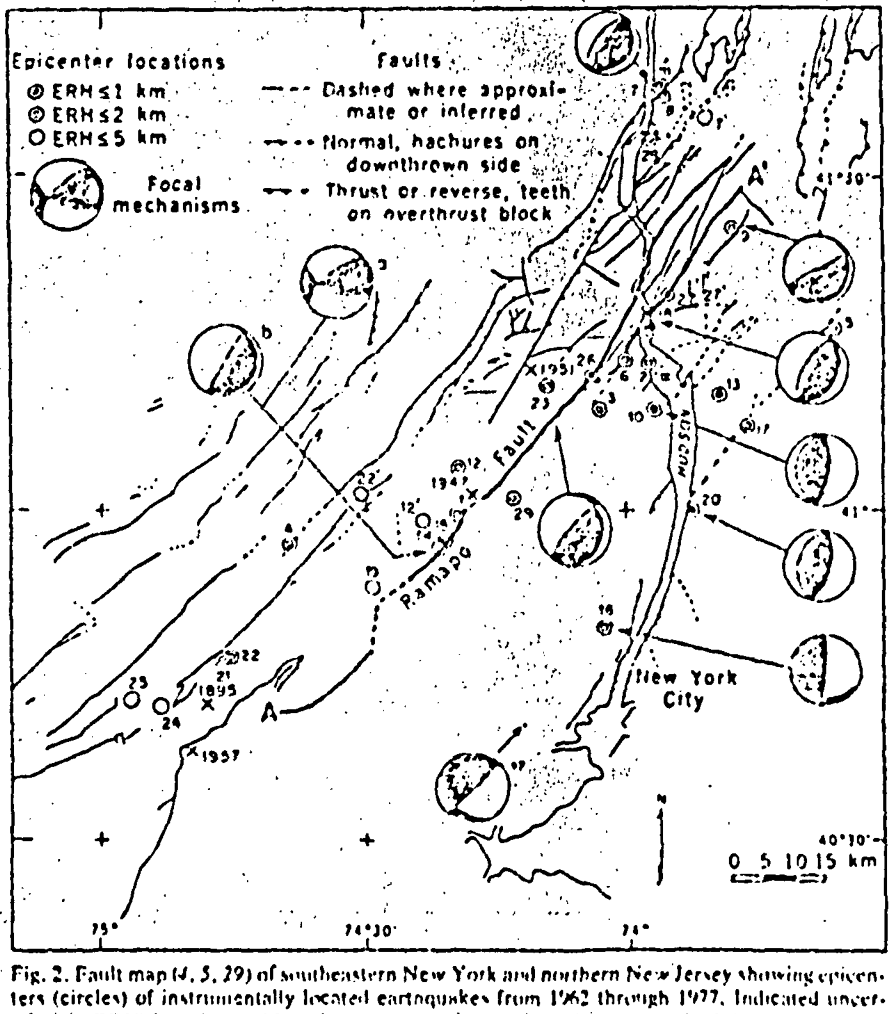

Fig. 2. Fault map (4, 5, 29) of southeastern New York and northern New Jersey showing epicenters (circles) of instrumentally located earthquakes from 1962 through 1977. Indicated uncertainties (*ERH*) in epicentral locations represent approximately two standard deviations. Focal mechanism solutions are upper-hemisphere plots; the dark area represents the compressional quadrant. For event 11 there are two possible focal mechanism solutions; the data, however, [illegible]

trending faults.

Although the instrumentally located events in Fig. 2 are small in magnitude and cover only a 15-year time span, the historic record of felt shocks shows that much larger earthquakes have occurred in the greater New York City area. Among the larger events known to have occurred during the last 250 years are three shocks (1737, 1884, and 1927) of intensity VII on the modified Mercalli (MM) scale and three (1783, 1895, and 1957) of intensity VI. Since precisely located shocks of the last 15 years show such a close relationship to northeast-trending faults, the larger felt shocks, for most of which precise locations are not available, are most reasonably interpreted as occurring along the same faults. In other areas where a longer record of instrumental locations is available, larger shocks show an even greater tendency than smaller shocks to be localized on major throughgoing faults (15).

Large uncertainties are inherent in efforts to locate earthquakes solely from felt reports (9); consequently, the larger events cannot be unequivocally associated with a specific fault. Within the uncertainty in the data, however, some of these events may have occurred on the Ramapo fault. The 1884 shock was felt from Maryland to New Hampshire; fallen bricks and cracked plaster were reported at 30 sites from eastern Pennsylvania to central Connecticut. Although two recent catalogs (9, 16) place the epicenter in Brooklyn, New York, both list Rockwood (17) as their original source of data. He placed the center of the zone of maximum shaking in northeastern New Jersey. An epicentral location in that area is supported by newspaper reports of foreshocks that were felt in Paterson, New Jersey (18). Felt reports for the 1737 shock are much more limited. The smaller felt area of the 1927 event places it somewhere along the north shore of New Jersey near Asbury Park, well off the Ramapo fault.

Felt reports for shocks in 1895 and 1957 and limited instrumental data for 1957 (m_b = 4.4) indicate that they occurred near the southwest end of the Ramapo fault near point A in Fig. 2. The 1783 earthquake was located by Smith (9) in New Jersey near the Ramapo fault. In addition, felt reports and limited instrumental data indicate that an earthquake (m_b ~ 3.9) in 1951 occurred about 8 km northwest of the Ramapo fault and a shock of m_b = 3 in 1947 occurred on or close to the fault (Fig. 2).

Ramapo fault, and the history of felt shocks in the area, we conclude that the

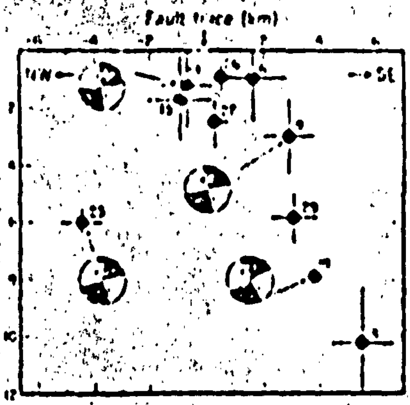

Fig. 3. Composite (stacked) vertical cross section showing focal depths and focal mechanism solutions (the dark area is the compressional quadrant) for events within 10 km of the Ramapo fault trace. The event number is keyed to the epicenter number in Fig. 2; only those events are plotted for which reliable focal depths could be determined. Bars represent one standard deviation. Northeast of epicenter 26 (Fig. 2) horizontal distance is measured from one of two major branches of the fault on the basis of focal mechanism solutions.

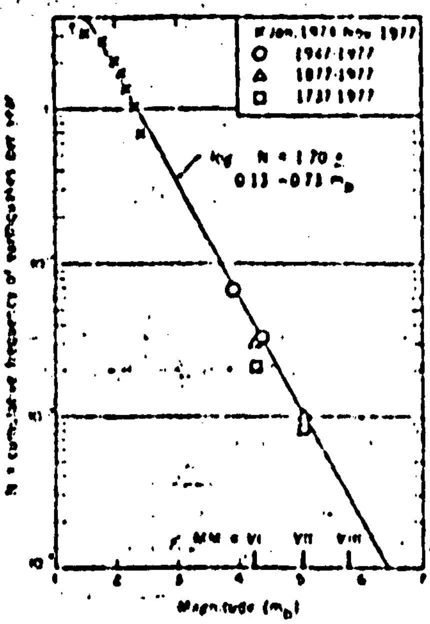

Fig. 4. Cumulative number (N) of earthquakes of magnitude m_b or greater per year as a function of magnitude. Data sets are each for the 120-km-long segment of the Ramapo fault and for shocks located within 10 km of the fault. The question mark denotes the minimum value, that is, the incomplete detectability of events of that magnitude. The slope of the curve, 0.73, was determined independently for recent shocks in New York and adjacent areas. The intensity-magnitude relationship is from (19). The uncertainty, ± 0.13, in the value of a (log N = a − bm_b) represents the 95 percent confidence interval.

maximum design earthquake of the Indian Point reactors. The relatively short period of historical data (about 250 years) is not sufficient to establish an upper bound to the size of shocks for a particular region unless some geologic or tectonic criteria are invoked.

Perhaps the most important question involving earthquakes and the seismic safety of Indian Point is: How active is the Ramapo fault? We calculate the probability of occurrence (Fig. 4) of earthquakes of intensity VII and VIII within 10 km of the fault by extrapolating the occurrence of smaller shocks to larger magnitudes using the well-known relationship log $N = a - bM$, where N is the cumulative frequency of shocks, M is the magnitude, and a and b are constants. The b value, 0.73, was obtained for shocks recorded throughout New York and New Jersey (10) and is assumed to be applicable to this subregion. The ×'s in Fig. 4 represent the rate of occurrence of shocks within 10 km of the Ramapo fault between points A and A' that occurred from 1974 to 1977. We fitted the solid line through the ×'s, using the slope 0.73.

To check the predictability of the frequency-magnitude relationship thus determined, the rates of occurrence of historical events discussed earlier are shown in Fig. 2 for three different periods. We estimated the magnitudes of the historical events from the following relation between intensity (I) and magnitude: $m_b = -0.20 \pm 0.05 + (0.75 \pm 0.03)I$ for the East Coast (19). The rates of occurrence of events for the periods 1962 to 1977 (1951 and 1957 earthquakes) and 1887 to 1977 (1957, 1895, and 1884 earthquakes) are in excellent agreement with those predicted by the solid line (Fig. 4). Squares (Fig. 4) indicate the rate of occurrence of events up to intensity VII for the period 1737 through 1977 if both the 1737 and 1884 (MM VII) earthquakes occurred on or near the fault.

For the entire fault, the relationship between N and m_b predicts shocks of MM ≥ VII about once per 97 years if no upper bound is placed on the maximum size of possible earthquakes. If, however, we assume that shocks of MM ≥ IX or MM ≥ VIII cannot occur, then the corresponding recurrence times for MM ≥ VII are about 105 and ... years. These estimates are subject to possible systematic errors in determining magnitude, to uncertainties in the relation between m_b and I and the b value, and to possible errors in extrapolation

Method	Estimated recurrence time (years)		Probability for exposure interval of 40 years (%)	
	VII	VIII	VII	VIII
1. Earthquake frequency-magnitude relationship (Fig. 4)				
a. Events within 10 km of site only:				
No upper bound on size of events	580	2050	6.7	2.0
Excluding events of MM ≥ IX	630	2870	6.1	1.4
Excluding events of MM ≥ VIII	810		4.8	
b. Events along entire Ramapo fault:				
No upper bound on size of events	300	1050	12.5	3.7
Excluding events of MM ≥ IX	340	1880	11.1	2.1
Excluding events of MM ≥ VIII	530		7.3	
2. MM VII shocks occur at random once per 100 years along faults of total length 360 km	1800		2.2	
3. Probabilistic calculation by McGuire (20) based on historic events				
a. No upper bound on size of events	1000	3160	3.9	1.3
b. Excluding events of MM ≥ IX	2240	7080	1.8	0.6

the data to larger magnitudes. We estimate that they may be uncertain by a factor of 2 to 3.

Using this log N-m_b relationship, we derive in Table 1 (method 1) the recurrence times for MM intensities at the reactor site to equal or exceed intensities VII and VIII, for three different upper bounds on the size of possible earthquakes. The corresponding probabilities of equaling or exceeding intensities VII and VIII for an exposure interval of 40 years, the presumed lifetime of the nuclear power plants, are also tabulated.

First (method 1a) we calculate the contributions to site intensities only from earthquakes within 10 km of the site. The intensity at a distance of up to 10 km, for earthquakes of moderate size, is expected to be nearly the same as that at the epicenter (20). Thus, the probability that site intensity will equal or exceed, say, VII once in 40 years from earthquakes within 10 km of the site is equivalent to the probability of occurrence of earthquakes of MM ≥ VII. For an earthquake more distant than 10 km the probability that its intensity at the site will equal or exceed a given intensity is a function of the size of the earthquake and the decay of intensity with distance. Approximating the fault zone as a line source, and assuming the intensity-distance relationship of McGuire (20) for the East Coast, we used the procedure developed by Cornell (21) in method 1b (Table 1) to integrate over the entire fault length. The probabilities of equaling or exceeding intensities VII and VIII thus calculated are not greatly affected by the use of a line instead of an areal source

but are sensitive to the intensity-distance relationship. Other attenuation curves (22), also considered appropriate for the eastern United States, give higher estimates than those in Table 1 (method 1b).

Table 1 shows that the calculated probabilities are not greatly dependent on the maximum size of earthquakes. Estimates obtained by excluding events of MM ≥ IX, however, are probably more realistic. Thus, the probability that the MM intensity at the reactor site will equal or exceed VII, the design (safe shutdown) earthquake, once in 40 years is about 5 to 11 percent. For MM ≥ VIII, the probability is about 2 percent.

Method 2 (Table 1) is a more approximate calculation based on the historic rate of occurrence of shocks of intensity VII in the greater New York City area. We take the rate as 2.5 shocks per 250 years since the 1927 event is assigned MM VII in one catalog (16) and VI in another (9). We assume that these shocks, like those in Fig. 2, occur along major northeast-trending faults, which we estimate have a total length about three times that of the Ramapo fault. Assuming a rupture length of about 5 km for MM VII (23), we obtain a total of 72 rupture segments, four of which we take as being within 10 km of Indian Point. This gives a recurrence time of 1800 years for MM VII within 10 km of the plants. This calculation suffers from our poor knowledge of the lengths of rupture zones for eastern earthquakes and of their extent in depth. Since precisely located shocks in the area have computed depths that are less than 11 km, the calculated recurrence time is not greatly affected by the

shocks.

McGuire (20) calculated probab... for exceeding given intensities for a n... ber of sites near the East Coast by ... domly varying the locations of hist... shocks within individual seismic pr... inces. He showed that his metho... stable to uncertainties in the design... of seismic provinces and the size of ... cific shocks. The approach used in ... federal siting appendix (7), however ... highly sensitive to those parameters. ... ferences of up to two MM intensity u... can be obtained with the existing pro... dure, depending on how the seis... provinces are drawn. For a 10,000-y... return period, McGuire calculated ... shock of intensity 8.3 for New York C... under the assumption that shocks la... than MM IX cannot occur. If his res... are applied to Indian Point, we obtain ... turn periods of 2240 and 7080 y... (method 3, Table 1) for intensities ... and VIII, respectively. Some of his ea... calculations, which probably are no... realistic as the above, yield shorter ... turn periods for the same intensities.

We think that method 1 provides ... most realistic estimate since it is ba... on data from the area of the Ram... fault, whereas in method 3 a random d... tribution of activity in space is assum... Our best estimates are larger by abou... factor of 10 than that computed by ... seismologists (24) for the same intensi... their estimate suffers from an assum... random distribution of activity in s... and much more limited data than ... used in this study. The 5 to 11 perc... probabilities we obtained, of cou... should not be equated with the probabi... ty of significant damage or accidental ... dioactive release.

Indian Point reactors 2 and 3 are ... signed for an input acceleration of ... percent of the earth's gravitational acc... eration, g (25), for very high frequenc... The power plants, however, are situa... within a few kilometers of branches ... the Ramapo fault system, where ea... quakes as shallow as 1 to 2 km occ... Now that we have demonstrated that ... Ramapo fault is active, it is not cl... whether nearfield accelerations, wh... can be as high as 0.5g at high frequen... for moderate-size earthquakes (26), ha... been adequately considered in the de... of the reactors. The Advisory C... mittee on Reactor Safety of NRC rece... ly recommended a minimum design of ... percent of g for new reactors in the ... (27).

We believe that our calculations p... vide the public and policy-makers ...

many of the approximately 70 nuclear power plants now in operation in the United States can be allowed to operate at a risk of 5 to 11 percent without the probability becoming high that shaking will exceed that of the design earthquake for at least one of them over a 40-year period.

The Indian Point seismic hearings before NRC brought out a number of problems about the applicability of the existing federal regulations (7) to sites in the East. By these regulations a capable fault is defined on the basis of either (i) demonstrated fault movement younger than 500,000 years or (ii) macroseismicity instrumentally determined with records of sufficient precision to demonstrate a direct relationship with the fault. There is no evidence for surface breakage in any earthquake in the central or eastern United States, with the possible exception of questionable ground breakage during the New Madrid, Missouri, earthquakes of 1811–1812. Yet we know that a number of large and damaging shocks have occurred in these areas. The Ramapo fault is typical of many eastern sites in that almost all of the rocks in the region, with the exception of scattered postglacial deposits less than 15,000 years old, are older than 150×10^6 years. Hence, it is very difficult to tell if earth movements are as old as 150×10^6 years or if they happened in the past 0.5×10^6 years. Thus, surface breakage is not a good indicator of either "capability" or seismic risk for many eastern sites.

The hearings demonstrated that the word "macroseismicity," which is not defined in the regulations, is rarely used or defined by seismologists. Various scientific witnesses differed to a large extent in their concept of macroseismicity (28). For much of the East, instrumental data of sufficient precision to demonstrate a relation to specific faults are very limited in time. Hence, it is not surprising that no fault in the central or eastern United States has as yet been declared legally capable.

In the absence of capable faults, the concept of "tectonic provinces" is used in deriving the intensity of the design earthquake from the historic record of shocks. The intensity at the site is calculated by moving historic shocks in the same province to the site and shocks in adjacent provinces to the closest point within those provinces (if the shocks cannot reasonably be correlated with a [illegible] allowed only if reasonably large tectonic provinces are used. At the Indian Point hearings it was clear that the scientific witnesses had greatly varying opinions about the size, designation, and concept of tectonic provinces (28). These ambiguities can result in a number of small provinces being invoked to keep critical historic shocks at a distance such that their intensities at the site are much lower than those near the epicenter. In the case of Indian Point, this leads to a design earthquake of intensity VII or VIII depending on the designation of tectonic provinces.

The rate of seismic activity along the Ramapo fault and in the East in general is clearly less than that for major faults in, say, California or Japan. Although the federal siting regulations put the question of the capability of a fault as a yes-no decision, the present rate of movement along faults obviously varies by many orders of magnitude. We believe recognition must be given to the fact that some faults are more "capable" than others. Until this is done, the public may well equate the designation of capability with size and rate of occurrence of earthquakes like those along, say, the San Andreas fault in California. In the context of siting nuclear power plants and other critical facilities, we believe that the rate of activity must be judged in comparison to the design earthquake of the plant. The rate of activity along the Ramapo fault is such that it probably only warrants concern for critical facilities such as nuclear power plants and hospitals for which integrity must be ensured at a high level of confidence.

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