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Volcanic and seismic hazards at a proposed nuclear power site in central Java

Alexander R. McBirney^{a,*}, Leonello Serva^b, M. Guerra^b,
Charles B. Connor^c

^a Department of Geological Sciences, University of Oregon, Eugene, OR 97403, USA

^b APAT, Italian Agency for Environment Protection and Technical Services, Via Vitaliano Brancati, 48, 00144 Roma, Italy

^c Department of Geology, University of South Florida, 4202 East Fowler Avenue, SCA 528, Tampa, FL 33620-5201, USA

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Abstract

A nuclear power plant site has been proposed near the base of Mount Muria, a long-dormant volcano in Indonesia. Over a period of eight years the volcanic and seismic hazards were investigated, first by the contractor and later by a joint team of Indonesian geologists and consultants to the International Atomic Energy Agency. In order to assess the risk posed by a large volcano for which there is no record of historical eruptions, it was necessary to determine the age of the last activity by geological and geochronological means and to deduce from this whether the volcano posed a credible risk. Similarly, because there was no adequate record of seismic activity, the seismic hazards were investigated mainly by geological, geomorphological, and geophysical methods that identified and characterized potential seismogenic sources related to the volcano or tectonic movements (i.e. active/capable faults). Muria Volcano has not erupted since about two thousand years ago, but the last activity was sufficiently recent to rule out any assumption that the volcano is extinct. Detailed studies indicated that the proposed site may be vulnerable to the effects of air-borne tephra, pyroclastic flows and surges, debris flows, lahars, and opening of new vents. A more serious factor, however, was the poor geotechnical properties of the foundation material that required a careful analysis of the seismic hazards. Although the project was suspended, the study proved useful, because it provided an opportunity to develop procedures and techniques that could be applied in similar studies elsewhere.

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1. Introduction

1.1. Background of study

In 1991 the Indonesian government invited the International Atomic Energy Agency (IAEA) to

evaluate safety studies for what was to be Indonesia's first nuclear power plant. Because the site is in a densely populated region on the north coast of Java near one of the world's major chains of active volcanoes (Fig. 1), the primary concern of the safety studies was the potential hazards of

* Corresponding author. E-mail address: mcbirney@darkwing.uoregon.edu (A.R. McBirney).

volcanism and seismicity. A panel of geologists, volcanologists, geophysicists, and engineers reviewed the geological studies and found a number of open issues critical to the acceptability of the proposed site. Additional studies were recommended to address these concerns, and with time, the panel took on an increasing role in the investigation until it had a team of eleven experts from various nations working in close cooperation with Indonesian scientists.

Having no established precedent for assessing volcanic hazards under these conditions, the team developed a plan of study that could be

adapted for use at other projects of this kind. The result was a set of guidelines laid out in the 1997 IAEA document ‘Volcanoes and associated topics in relation to nuclear power plant siting’ (McBirney and Godoy, 2003). The guidelines are similar to others that had already been prepared for earthquakes, tsunamis, and other natural hazards. A preliminary version was distributed to all appropriate members of the United Nations, and recommended changes and additions from experts in several of these countries were incorporated into the final version. Our purpose here is to show how this approach was followed in the

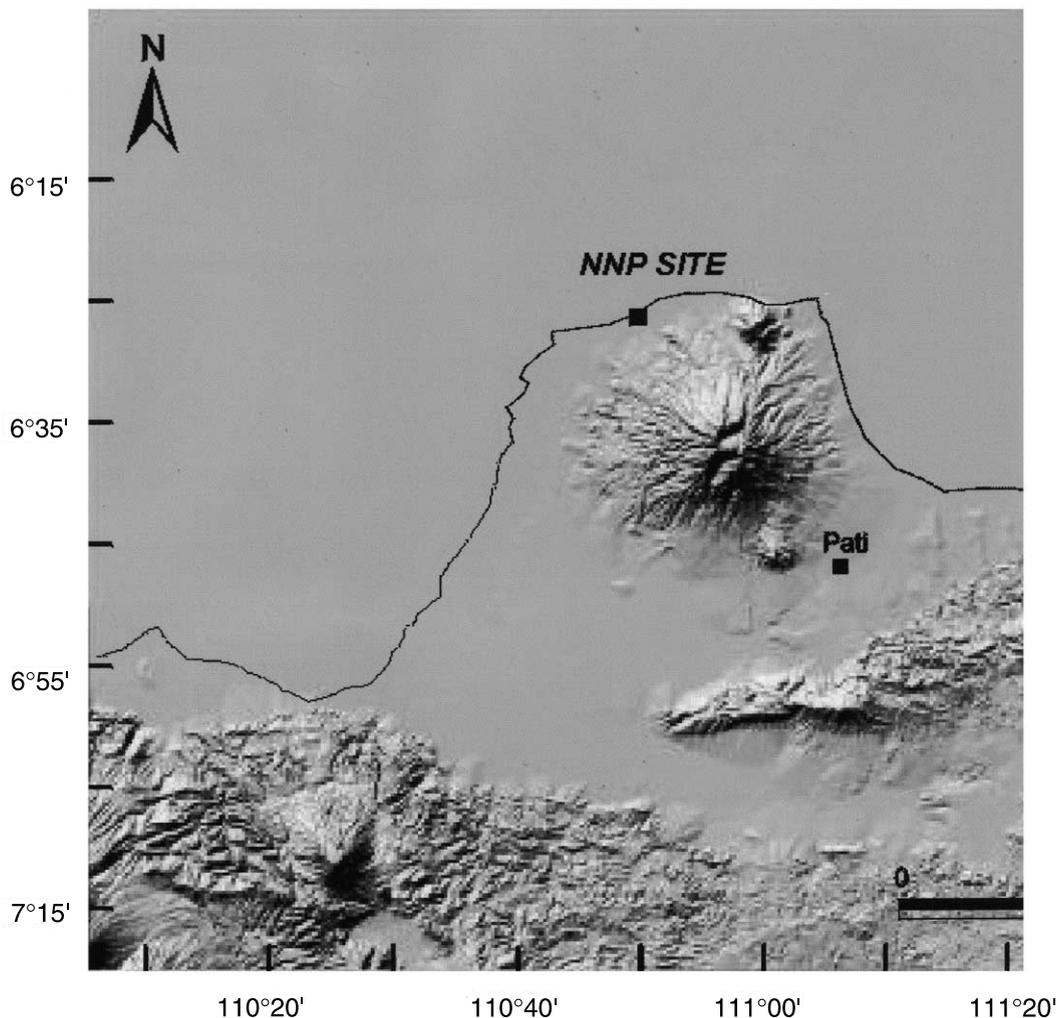


Fig. 1. Satellite image showing the location of the proposed nuclear power plant (NPP) with respect to Muria Volcano.

case of the proposed Indonesian nuclear power plant.

The investigation was concerned with a variety of possible hazards, but only those associated with volcanism and seismicity are discussed here. The data we report are taken from unpublished documents produced by BATAN (the Atomic Energy Commission of Indonesia), NEWJEC (a consulting company) and NTT (a team of Indonesian scientists from universities and public institutions formed with the specific goal of defining the seismic and volcanic hazards at the Muria site).

1.2. Volcanic and seismic hazards at nuclear facilities

Evaluations of seismic and volcanic hazards affecting nuclear facilities differ in several ways from other types of hazard assessments. The most important difference is that they are focused on hazards at a specific locality, in this case a proposed nuclear power plant site, rather than on a general region near a particular volcano or fault. In addition, one must consider volcanic and seismic hazards together, rather than independently, because they are closely linked. Seismicity is associated with most volcanic terrains and can induce mass movement on the slopes of the volcano, even without renewed magmatism. Because the assessment must consider the total hazard and risk, it must span both of these disciplines.

The success of volcanic hazard assessments depends on the quality of basic geologic research, numerical modelling of volcanic processes, and the investigators' experience with a great diversity of eruptive activities. Similarly, seismic hazard assessment requires a basic understanding of the regional tectonics, local fault characteristics, and site conditions. In our case, the team was faced with using information gathered by other groups, often with differing objectives. This inevitably complicated the task of providing adequate assessment of long-term geologic hazard rates. Such complications manifest themselves in the analysis as increased uncertainty.

The level of acceptable risk depends, of course, on the nature of the exposed facilities. For example, one does not hesitate to place scientific instru-

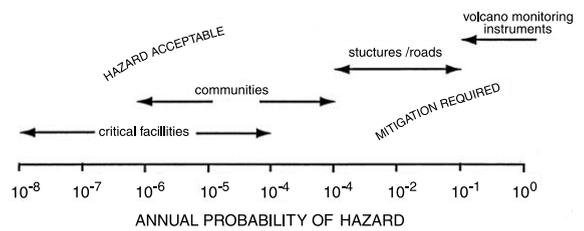


Fig. 2. The acceptable hazard varies greatly depending on the application. Critical facilities like nuclear power plants require the largest margin of safety.

ments in hazardous areas to monitor volcanoes, because the possibility of losing them is usually acceptable. Nuclear facilities occupy the opposite end of the spectrum (Fig. 2). The probabilities of volcanic eruptions or earthquakes resulting in loss of control of a nuclear plant, or in a release of radionuclides into the environment, must, of course, be very low, on the order of 10^{-8} to 10^{-6} per year, depending on the longevity of the facility. Note that at such low probabilities, uncertainties in assigning values to certain parameters, such as the frequency of volcanic eruptions, are very high. Estimates of hazards and risk based on a small number of events, either because these events are very infrequent or because they have not been recognized as such, are highly uncertain (Von Mises, 1957). Conversely, because the geologic record is usually incomplete, the small fraction of volcanic and seismic events that have been preserved in the geologic record may drive most of the risk analysis.

In its study of the Indonesian site, the team was not able to deal successfully with all of these issues. Nevertheless, the lessons learned there are worth considering, in the hope that future assessments will avoid some of the pitfalls we encountered.

1.3. Plan of investigation

Hazards were considered on all scales ranging from the broad regional tectonic setting to conditions in the immediate vicinity of the site. As outlined in McBirney and Godoy, 2003, the goal of the regional studies was to identify all Quaternary volcanic and seismic phenomena within a radius

of at least 150 km from the site on Muria Peninsula.

Because of its great geological interest, the Indonesian Arc has been the subject of countless volcanological and seismological studies the results of which are available in publications dating back more than a century. With so much information already compiled, much of the research required on the regional scale could be accomplished by a review of the existing literature. Unfortunately, however, these resources are mainly of a general nature and are not adequate for many aspects of a detailed study of the present kind. It was necessary, therefore, to acquire additional information directly related to the project.

The objectives of this phase of the study were to: (1) characterize the tectonic setting and analyze the nature of Pliocene and Quaternary volcanism in the Indonesian Arc; (2) establish a seis-

motectonic model for interpreting the seismicity near the site; (3) compile a record of activity for all active volcanoes and faults within a radius of 150 km from the site; and (4) identify time-stratigraphic units and determine the ages of the Pliocene and Quaternary volcanic deposits having a regional extent of 100 km² or more.

These regional studies were followed by investigations on a more detailed scale of conditions in the vicinity of the proposed site. The potential hazards were grouped into two categories depending on whether or not they could be mitigated by economically feasible design measures: (A) volcanic or seismic hazards that adversely affect the stability of the site to the degree that the site could not be accepted under any conditions, and (B) conditions that can be accommodated through appropriate design standards incorporated into the plans for construction.

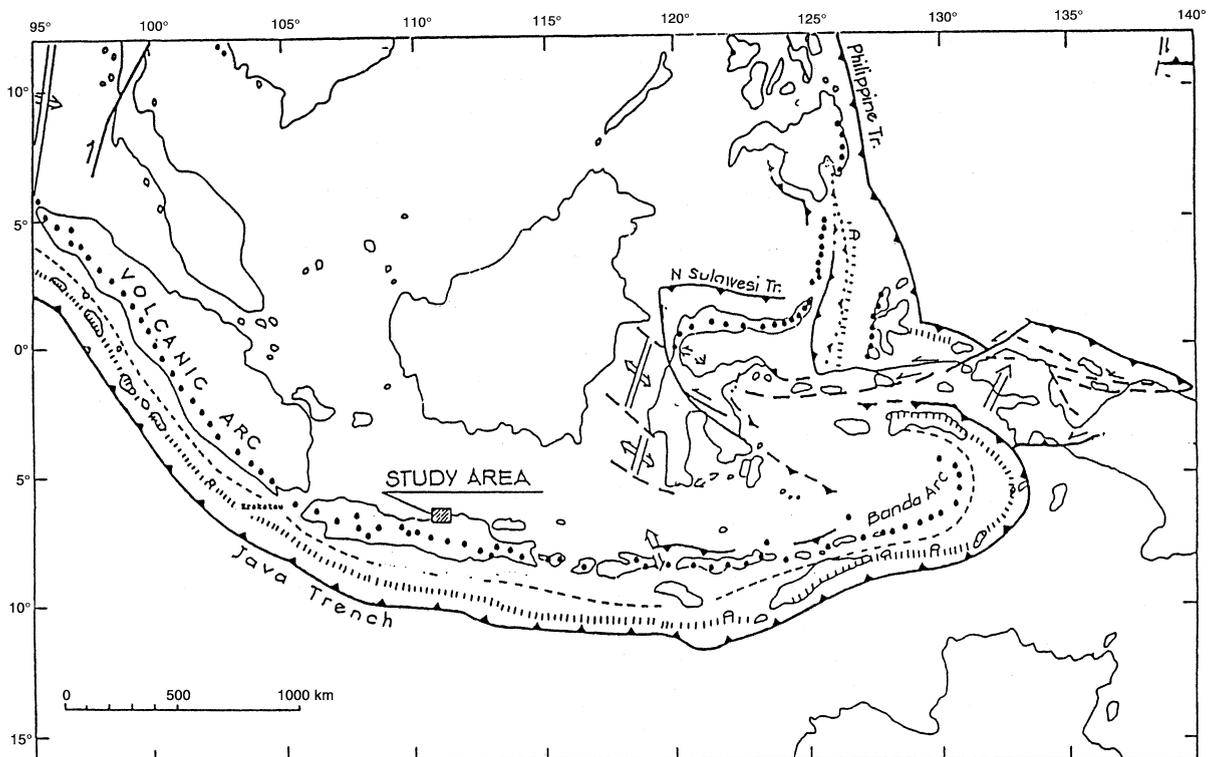


Fig. 3. Regional setting of the proposed Indonesian nuclear power plant.

2. Investigations of volcanic hazards

2.1. Regional volcanism

Volcanism in the Indonesian Arc is closely associated with the subduction of the Indian Plate from the Java Trench northeastward beneath Sumatra and Java (Fig. 3). The depth of the Benioff Zone increases from about 175 km beneath the main volcanic arc to approximately 400 km beneath the proposed site on Muria Peninsula.

The main axis of the volcanic front extends 600 km along the length of the Indonesian Arc. The volcanoes of the main chain are typically strato-volcanoes, dome complexes, and calderas consisting of calc-alkaline lavas, lahars, and pyroclastic rocks. Widely scattered volcanoes behind the main chain tend to be somewhat smaller cones of potassic composition. Their activity is less frequent than that of the main chain.

Of the 35 youthful volcanoes on the island of Java, 22 have had recorded eruptions since 1600. Of the seven volcanoes located within 150 km from the site (Fig. 4), five (Merbabu, Merapi, Dieng, Sumbing, and Sundoro) have erupted within this same period. Although no recognizable tephra

ra from these volcanoes has been identified on Muria Peninsula, its recently active volcanoes are potential sources of volcanic ash that could reach the proposed site.

2.2. Conditions in the vicinity of the site

The investigation of the region closer to the site identified three volcanic centers: Muria Volcano, Genuk Volcano and Mt. Patiayam.

Muria Volcano (elevation 1625 m) is a large composite cone composed of lavas, tephra and shallow intrusive rocks of highly potassic character. Much of the constructional form of the volcano is still preserved, but the flanks have been deeply incised by erosion. The central vent complex consists of several craters up to 5 km in diameter. These are aligned along a north–south trend. Approximately 25 smaller vents occur on the flanks. These include several small domes on the upper flanks of the volcano and within the older central vents. Numerous cinder cones and associated lava flows have been identified at various elevations on the flanks. These include two low-rimmed craters, Gunung Rowo and Bambang, located on the upper southeastern and

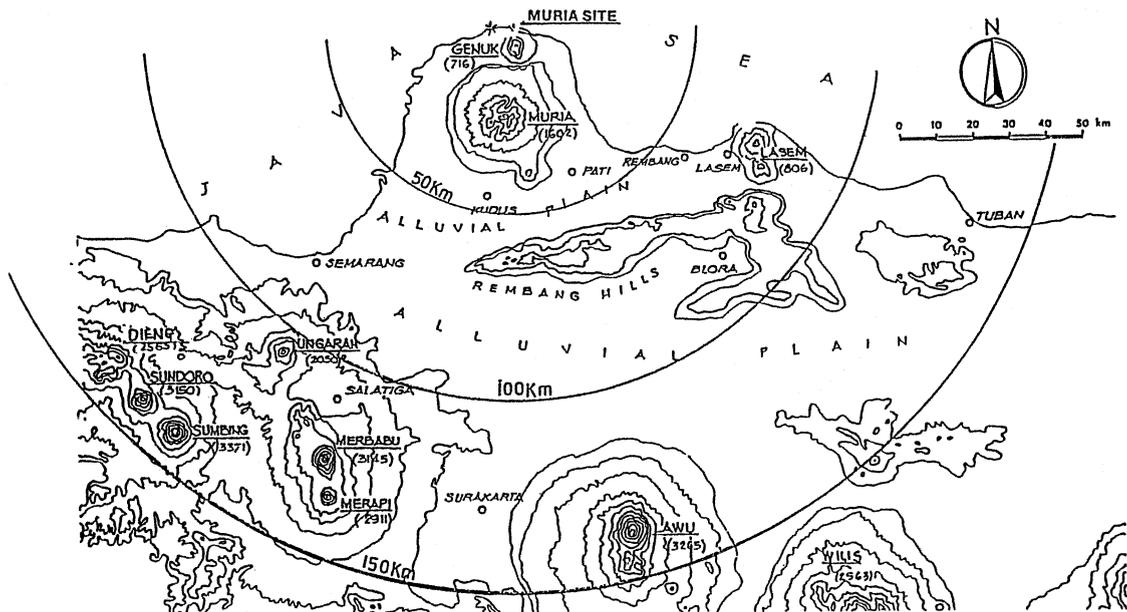


Fig. 4. Volcanoes within a distance of 150 km of the proposed site.

northeastern flanks, respectively. Gembang, a third youthful explosion crater near the southeastern base of the volcano, has been partly filled by lava that descended from higher on the flanks of Muria

Genuk Volcano (elevation 670 m) is an eroded dome complex situated at the northern base of Muria. It stands on a thick series of tuffaceous Pliocene mudstones and shallow marine limestones. Low-temperature gas emissions have been found on the western flanks of the volcano. (These emissions are discussed below.)

Mt. Patiayam (elevation 350 m) is located 17 km south-southeast of Muria. It is a broad dome-like structure covered almost entirely by lacustrine beds that appear to have been upwarped by one or more shallow intrusions. Small exposures of lava and breccia can be found in erosional channels that have cut through the overlying sediments.

Muria and Genuk volcanoes have been studied by van Bemmelen (1947), Boomgaart (1947), Nicholls and Whitford (1983) and Maury et al. (1987). Their work described the eruptive products as potassic basalts, basanites, tephrites, trachytes, and phonolites. No regular compositional progression has been identified, but the later rocks tend to be more potassic and silica-deficient. The magmatic activity has been divided into five major episodes. In descending order of age, these are: (1) first Genuk stage; (2) first Muria stage; (3) middle Muria stage; (4) younger Genuk stage; and (5) younger Muria stage.

A combination of stratigraphic evidence and 74 radiometric age determinations show that activity of Genuk began with shallow submarine eruptions at least 2 million years ago and continued until about 1.65 million years ago. Muria first became active about 0.84 million years ago but there seems to have been a hiatus lasting tens of thousands of years beginning about 0.8 million years ago. At that time, the area was still under water, and the sedimentary deposits of that period contain little if any contemporary volcanic material. Genuk became active again during this period and continued until about 0.49 million years ago, while Muria had strong renewed activity until 0.32 million years ago. The younger Muria

stage produced several pyroclastic flows that descended the northwestern flank of the volcano.

The most recent known activity produced three explosion craters and at least one lava flow on the eastern flanks of Muria. In early site investigations, the three water-filled craters were variably and inappropriately described, first as man-made reservoirs, then as fluvial meanders, and later as accumulations of marine sediments around depressions of unknown origin. Their volcanic nature is clearly evident in the morphology of the crater rims and certain features of the deposits, such as accretionary lapilli, bomb sags, and surge deposits that are characteristic of phreatomagmatic eruptions. The well-preserved morphology of these maars is in sharp contrast with the generally eroded and deeply weathered slopes of Muria Volcano, so a special effort was made to determine their age.

Carbon-14 dating of the red paleosol underlying the maar deposits yielded maximum ages of 6230 ± 530 yr for Gunung Rowo and 2110 ± 360 yr for Bambang. A fission-track analysis of zircon crystals in a pyroclastic layer resting directly on the paleosol gave ages of 0.10 ± 0.04 Ma and 0.11 ± 0.05 Ma for Gunung Rowo. The ^{14}C ages were considered unreliable because of possible contamination with young organic material, and there was doubt whether the fission-track ages corresponded to the age of the eruptions or to that of older material that they brought to the surface from greater depths. The normal scarcity of zircons in volcanic rocks makes the latter possibility more likely. Moreover, the zircons are found in a tephra layer that lies between the paleosol and the overlying beds and may therefore have come from an eruption at an unrelated vent. It might be possible to date fragments of glass in the upper pyroclastic deposits either by radiometric methods or by measuring the thickness of the hydration rims, but work was suspended before this could be attempted. The only firm conclusion that could be drawn is that the maars may be as young as a few thousand years.

2.3. *Volcano capability*

The first step in the volcanic hazard investiga-

tion was to determine whether any of these volcanoes in the vicinity of the site might be capable of future activity affecting the proposed power plant. The concept of a capable volcano, like a capable fault, can be used to distinguish those features that are potentially hazardous from those that are not. There are several terms, such as 'active', 'dormant', and 'extinct' that have been used for this purpose, but these adjectives are of limited use in volcanic hazard assessment because of the great latitude in their definitions, even among volcanologists. Furthermore, other types of activity, such as landslides and debris flows, can contribute as much to the risk as certain common types of eruptions. Unlike 'active' and 'dormant', the term 'capable' is used for volcanoes that pose any kind of risk, even if they do not erupt. A volcano may be a potential source of lava, ash, or other disruptive phenomena, but it is not considered capable unless this activity can affect a given location or installation. This latter factor must be determined independently.

The criteria for assessing the capability of a volcano are hierarchical. Obviously, historical activity at a volcano that is within an effective distance of the locality under consideration is a clear indication that it is capable. In the absence of historical eruptions or current manifestations of volcanic activity, a sequence of tests is applied. A detailed assessment of volcanic hazards is called for if one or more of these criteria are met. If none is found, no further investigation would be required. In the case of the Muria–Genuk complex, the initial studies took two forms.

(1) The record of volcanism was examined to determine whether any of the volcanic centers had historical eruptive activity. The search revealed no record of eruptions from any volcano on Muria Peninsula.

(2) The volcanoes and an area of 100 km² around the site were examined to determine whether there were any manifestations of current magmatic activity. Seismic records were examined for evidence of greater than normal seismicity. Temperature gradients of 5–6°C per 100 m were measured in boreholes extending to depths of about 250 m near the site. These temperature gradients were considered normal for the region. No

evidence of large-scale hydrothermal activity could be found on any of the major volcanoes, but gas emissions in springs on and around Muria and Genuk volcanoes and in a bore hole 1.5 km from the site drew attention to the possibility of emanations from a magmatic source at shallow depths. The gases were analyzed to determine whether they included magmatic components that might indicate a shallow source of magma capable of producing other types of volcanic phenomena. In addition, a voluminous discharge of toxic gases could endanger human life as happened nearby at Dieng in 1979 when 156 persons died of asphyxiation (LeGuern and Tazieff, 1982). Such an event on Muria Peninsula would obviously have an adverse effect on the safe operation of the plant.

Gas samples were taken from the soil in a grid pattern covering an area of 5 km² around the proposed site. Analyses showed that the gases are rich in methane (CH₄) and carbon dioxide (CO₂), much of which was initially thought to be derived from shallow organic material and sea water. These components are not present in toxic concentrations, because the large amounts of meteoric water circulating through the permeable sediments dilute any volcanic gases reaching shallow depths. Nevertheless, the amounts of gas given off could be much greater if it were released during a phreatic or phreatomagmatic eruption.

Analyses showed that the helium in the samples had isotopic ratios (R/R_a) ranging from 6.19 to 7.13. This is a significantly larger ratio than that in non-volcanic gases (1.65–2.63) but similar to the ratio of mantle-derived helium from sources such as mid-oceanic spreading ridges (R/R_a = 6–8; Craig et al., 1980). Similarly, the carbon was found to have a δ¹³C/¹²C value of –4.0 to –2.8. This is within the normal range of magmatic carbon (–10 to 0) and distinctly different from that of non-magmatic carbon (–30 to –10). Gases are therefore an important consideration in assessing the possibility of a volcanic eruption near a site.

(3) The morphology of the volcanoes was examined for evidence of recent, non-eruptive mass movements. Remnants of debris flows and ava-

lanches were found on the slopes of Muria, and lahars were encountered at numerous locations on the surface and in boreholes near the proposed site. A ground magnetic survey of the site area revealed complex magnetic anomalies in low-lying areas about the site. These were interpreted as resulting from blocks a meter or more in diameter buried in the shallow subsurface. As such, they offer further evidence that the site was affected by lahars or similar mass movements, e.g. debris flows and avalanches. No reliable radiometric ages have yet been obtained for these flows.

(4) The geological history of the volcanic centers was examined to determine whether there was any evidence that the time elapsed since the last volcanic activity was significantly shorter than the maximum known repose interval for each individual volcano. Because the record of volcanic activity was considered incomplete, this test was indeterminate.

(5) The eruptive history of similar volcanoes elsewhere was examined to determine whether the time elapsed since the last volcanic activity was significantly longer than the maximum known repose interval for volcanoes of a similar type. A review of subduction related potassic volcanoes in the back-arc region of Italy showed that some of these volcanoes appear to have erupted after repose intervals of 100 000 years or more. The well-preserved morphology of the youthful explosion craters on the flanks of Muria indicate that they were probably formed within the last few thousand years and certainly less than 100 000 years ago.

Thus, at least three of the tests indicated that a further, more thorough, investigation of potential volcanic hazards was warranted. A program was laid out and each type of hazard was studied in greater detail.

3. Detailed volcanic studies

A detailed survey was undertaken to describe the geology of an area of approximately 100 km² centered on the proposed site. Each type of hazard was evaluated in terms of a screening distance value (SDV) corresponding to the maximum

distance from the source to the site at which the phenomenon could be a hazard. The method was used for all phenomena such as ballistic projectiles, tephra accumulation, lavas, pyroclastic flows, lahars and debris flows, that can be related to specific sources. Those types of hazards that cannot be assigned a screening distance were treated independently by other means.

The concept of screening distances was developed in seismic risk assessment for sensitive sites, such as nuclear power plants, that must be located in areas of very low geologic risk. SDVs have proved to be very useful for such purposes because they offer a way of arriving at realistic assessments of hazards based on a conservative worst-case scenario for the potential impact of each type of hazard. Volcanologists are usually reluctant to convey worst-case scenarios in this way because of a fear, often well-founded, that they will be misinterpreted as ‘base case’ or ‘expected’ scenarios. Conversely, worst-case scenarios can be overly conservative. Nevertheless, for very sensitive conditions, e.g. those associated with nuclear installations, one cannot ignore the possibilities of large-magnitude events, even when these appear unlikely. Experience has shown that the method has two important advantages.

First, the effects of volcanic activity occasionally exceed all expectations based on previous experience. SDVs provide a method of illustrating potential hazards that appear very unlikely, because their effects extend beyond those of previous activity at a particular volcano or locality. For example, they take into account non-stochastic behavior such as that resulting from the geochemical evolution of a magmatic system. Second, screening distances are a useful regulatory tool. When appropriately constructed, they clearly distinguish areas where further assessments are needed from areas where further attention is unwarranted.

SDVs are derived by coupling source areas (e.g. volcanic vents, craters, calderas) to some attenuation function that shows the variations of potential impact over a given area. These attenuation functions are based on numerical simulations of large eruptions or the geologic records of analogous (or potentially analogous) volcanoes.

3.1. Ballistic projectiles

The IAEA guidelines set a screening distance of 5 km for the maximum range that material can be ejected on a ballistic trajectory. This distance was obtained from studies of past eruptions and theoretical principles such as those outlined by [Fudali and Melson \(1970\)](#) and [Wilson \(1972\)](#). It was determined that the Indonesian site lies outside this distance from any known vent.

3.2. Tephra accumulation

Several active volcanoes in the region, including Merapi and Merabu, could produce pyroclastic materials that may reach the site. Moreover, large amounts of tephra could come from the Muria complex if it were to return to its earlier level of activity. Although the summit of Muria is more than 20 km from the site, Genuk volcano and possible satellite vents on the flanks of Muria are much closer and could produce large amounts of tephra. Thus, the site is deemed to be within the screening distance for this type of hazard.

3.3. Lava flows

During the geological survey, two small outcrops of lava were found in stream beds about 9 km southwest of the proposed site. In addition, an andesitic lava 4.7 m thick was encountered in a borehole at a depth of about 40 m approximately 4.5 km south of the site. The proximity of these lavas raised the question of whether similar flows could reach the site during future eruptions. To evaluate this possibility, samples from these three localities were submitted for chemical analysis and radiometric age determinations. The major- and trace-element compositions of the two bulk-rock samples from stream beds were found to be the same within the precision of the analyses, but analyses of their plagioclase showed potassium contents of 5.6 and 1.2 percent K, respectively, and it was concluded that the two outcrops did not represent a single flow. One of the samples gave an Ar–Ar age of 0.090 ± 0.030 Ma and the other 0.637 ± 0.030 Ma, but dating of plagioclase separates from the same samples gave conflicting

results, and the age determinations were considered inconclusive. The age of the andesitic lava found in the bore hole has not yet been determined, but geophysical data suggested that this lava may be a block transported to the locality by a lahar.

An indication of the age of the most recent lava eruptions of Muria was deduced from a flow that descended the southeastern slope of the volcano and entered Gembang maar. This is one of the three youthful explosion craters mentioned in [Section 2.2](#). Because the flow is obviously younger than the maar it entered, it was concluded that lava had been erupted more recently than 100 000 years ago.

The distance that lavas can flow is a function of several factors including the composition and physical properties of the lava, the slope angle, vent geometry, and eruption rate ([Walker, 1973](#); [Kilburn and Luongo, 1993](#)). The initial studies utilized numerical simulations of the kind developed by [Ishihara et al. \(1990\)](#) and [Wadge et al. \(1994\)](#), assuming conditions appropriate for the lavas of Muria Volcano. The model was tested by reproducing a known lava that came within 4.5 km of the site. The simulations showed that this was close to the maximum distance such a flow could travel, so it was concluded that this could serve as a screening distance for this type of hazard and that the site was outside that distance for known vents.

3.4. Pyroclastic flows

The geological survey identified nine pyroclastic flows on the northwestern and southeastern slopes of Muria, but the rocks were too weathered to yield reliable radiometric ages. No pyroclastic flows were identified in boreholes near the site.

The initial studies set a screening distance of 11 km for pyroclastic flows on the basis that this was said to be the maximum distance that most historical flows had travelled. The IAEA panel considered this unrealistic, because many cases are known where they have flowed 25 km or more. No effective topographic barrier stands between the site and possible sources on the flanks of Muria Volcano, so it was concluded that the site is

within the screening distance for eruptions that produce large pyroclastic flows.

3.5. Lahars, debris flows and slope failures

Lahars are very common on the slopes of Muria. Some of the largest ones came within 2 km of the site. As in the case of the pyroclastic flows, the rocks were unsuitable for age determinations, but even if reliable ages could be obtained for clasts in these flows, they would not necessarily correspond to the age of the flow, because most lahars are made up of older debris caught up in slope failures.

The initial study set a screening distance of 15 km for lahars, but the 40–50-m-thick lahar found in boreholes at the site showed that this was not appropriate and that the site was indeed within the effective range of this type of hazard.

Other types of debris flows caused by large-scale slope failures, sector collapse, or comparable phenomena could not be identified in the geological studies, but examples of these phenomena on other Indonesian volcanoes indicate that if they occur they are unlikely to extend beyond a distance of about 15 km. The site is therefore considered to be outside the screening distance for this type of hazard.

3.6. Opening of new vents

The most recent activity of Muria was characterized by formation of new vents, including domes and the three explosion craters on the eastern flank of the volcano. Because new vents are known to have been formed as far as 25 km from the central vent of comparable volcanoes elsewhere, the site was considered to be within the screening distance for this type of hazard.

4. Probabilistic assessment of volcanic hazards

The studies described above identified two aspects of volcanic activity that should be assessed probabilistically. First, the probability of a large magnitude eruption from Muria Volcano had to be estimated, even though only scant information

was available for such an analysis. The study of the SDVs showed that a large eruption ($VEI \Rightarrow 5$) would certainly impact the site. Second, the probability of a new vent being formed within the vicinity of the site was estimated. New vents, including maars and cinder cones, would pose significant hazards and risk if they occurred within the vicinity of the site. As the most recent (Holocene?) activity in the Muria complex has been of this type, such an assessment is a key element in any evaluation of site safety.

4.1. Probability of future eruptions

The geologic record for the Muria region is quite difficult to cast in terms of such a probability density function, but the SDVs indicate that the site is potentially at risk from tephra fallout, lahars, and pyroclastic flows. A probability calculation is clearly warranted, provided, of course, that the uncertainties in the data set are propagated through this analysis. The probability of eruptions can be modelled as a Poisson distribution cast as the common ‘survivor’ function, where λ is the expected repose interval between eruptions:

$$f_x(x) = \frac{1}{\lambda} \exp(-x/\lambda) \quad (1)$$

Both λ and x are greater than 0. The probability of an eruption within a given time interval, say the 100-yr period since the last eruption is:

$$P[N \geq 1; 10000 \text{ yr}] = \int_0^{100} \frac{1}{\lambda} \exp(-x/\lambda) dx \quad (2)$$

and the probability that no eruptions will occur within this 100-yr interval is:

$$P[N \geq 0; 10000 \text{ yr}] = 1 - \int_0^{100} \frac{1}{\lambda} \exp(-x/\lambda) dx \quad (3)$$

Confidence in the expected repose interval also needs to be assessed. For this distribution and a confidence interval, λ :

$$\lambda = \left[\frac{n(n-1)\lambda}{\chi^2_{1-\alpha/2, 2n}}, \frac{n(n-1)\lambda}{\chi^2_{\alpha/2, 2n}} \right] \quad (4)$$

where n is the number of events used to estimate .

As a first step, consider the episodes of activity

at Genuk and Muria volcanoes shown in Table 1. Despite the large number of radiometric age determinations, there is still uncertainty about the timing of the major episodes of activity. Nevertheless, episodes of activity appear to have occurred at Genuk and/or Muria about 1.8, 0.8, 0.5, and 0.3 Ma. These major eruptive episodes, each of which produced voluminous deposits in the geologic record, clearly would adversely impact the site. In addition, there is clear evidence in the recent geologic record that smaller eruptions may have occurred between these major eruptive episodes. These smaller eruptions, such as the one that produced the Bambang maar, may or may not have been large enough to affect the site.

Considering only the large episodes, three repose intervals of major activity lasted 1.0, 0.3, and 0.2 m.y., respectively. The expected value for a repose interval is $\lambda \leq 0.5$ m.y., and the probability of a major new episode of volcanic activity at the site, during the next 100 years (a postulated performance period for the nuclear power plant) is $P[N \Rightarrow 1, 100 \text{ yr}] = 2 \times 10^{-4}$. Of course, there is considerable uncertainty in this estimate, given the few events on which it is based. With $2n =$ degrees of freedom and 95% confidence, $2.4 \text{ my} \leq \lambda \leq 0.2$ million years. In other words, there is about one order of magnitude uncertainty in λ . This corresponds to probabilities of major eruptive episodes impacting the site of 5×10^{-4} to 4×10^{-5} during the next 100 years. Of course the probability of smaller eruptive episodes in the next 100 years is larger, but it is less likely that these episodes would impact the site.

5. Investigations of seismic hazards

5.1. Introduction

Earthquakes in tectonically active volcanic regions can be divided into two general types: those associated with regional faulting of a purely tectonic nature and those related primarily to volcanic features. Because these two types of earthquakes have different characteristics, it is necessary to consider them independently when

assessing hazards in regions such as the Indonesian island arc.

The investigation for the proposed Indonesian nuclear power plant included a general survey of seismic and neotectonic activity that was designed to identify all potential seismogenic sources. These sources were then grouped into three categories: tectonic earthquakes related to recognizable faults, volcano-tectonic earthquakes associated with the volcanic phenomena described in the preceding section, and ‘back-ground earthquakes’ that cannot be assigned to any identified geologic features of tectonic or volcano-tectonic origin and could occur below the site.

The geological study was supplemented by seismic reflection profiles close to the shoreline and gravity and magnetic surveys designed to detect evidence of local ground movement or instability. Deformed sedimentary beds are exposed in nearby sea cliffs and gaps or discontinuities in the ages of sedimentary deposits were found in boreholes. These features, together with changes in the sequence of continental and marine facies, indicate important episodes of uplift and subsidence.

The seismological database for the Muria region was very poor, and no reliable earthquake catalogue was available. There had been very little useful investigation of primary historical or instrumental data for earthquakes occurring in the region. A crustal earthquake of magnitude 6.8 that occurred on December 12, 1880 (the Pati earthquake), 45–50 km from the proposed site, was a major concern. The main shock and aftershocks of December 14 were the strongest earthquakes recorded for this region. The record indicated events in the range of magnitude 4.5–5, but there was little information on their hypocenter locations or focal mechanism.

A record of instrumental seismicity was compiled using data from eight stations in three different networks that were operating on Muria Peninsula for different periods during the project. Two of the networks were designed to investigate seismicity associated primarily with the N–S feature running through Muria and Genuk volcanoes and the Rembang Depression (Fig. 5). The exact number of recorded events is not known but is of the order of several hundred and maximum

Table 1
Geological and lithologic features, as well as ages of potential vents recognized during field surveys

Name of vent	Geological features
Muria Crater I	This crater is located on the northernmost part of Muria peak and has a diameter of ~ 3 km and an elevation of 1575–1600 m above sea level (a.s.l.).
Muria Crater-II	Crater-II of Muria is the central crater of the volcano. This is the largest crater of Muria with dimensions of $\pm 7 \times 4$ km at an elevation of 1600 m a.s.l. It was the source of flank eruptions the products of which are mainly on the southwestern part of the summit.
Muria Crater-III	The crater is located on the southernmost side of the summit with an elevation of ± 1550 m a.s.l. This is the smallest crater, and has produced few eruption products (five mapped units).
Muria Crater-IV	Crater-IV is positioned on the boundary between Crater-I and Crater-II at an elevation of ± 1600 m a.s.l.
Bambang (maar)	Located 12 km northeast of the summit of Muria at an elevation of 300 m a.s.l. It has a diameter of 750 m. It was created by hydroclastic explosions the products of which cover paleosols of Pleistocene (?) age. The main products are poorly sorted subangular to angular fragments of sand to cobble size. Thin-bedding is seen in the upper part of surge deposits many of which are heavily weathered. Ejected bombs are randomly distributed within the bedding and are interpreted to be older rock fragments. Tuffs and volcanic breccias are also common. The age of the maar remains debatable. However, Ar/Ar dating gave the youngest plausible eruption age as 0.53 ± 0.01 Ma.
Gunung Rowo (maar) (MF-3)	Located on the southeastern flank of Muria at an elevation of 300–350 m a.s.l. A circular, monogenetic crater with a lake 15 m deep, and 1100 m in diameter. The height of the crater wall is 7–10 m. The deposits overlie paleosols and have the dune-like structure of base surge deposits and accretionary lapilli are abundant in some layers. Rock materials have subangular to angular shapes and pebble to cobble sizes. The paleosols are known to have an age of 10335 ± 430 yr indicating that the maar is younger than this.
Gembong (maar) (MF-1)	Located on the southwestern flank of Muria facing Patiayam at an elevation of 125 m a.s.l. It has an elongate shape of about 1×2.5 km. This crater is filled with water. Deposits are similar to those of Gunung Rowo maar. Sandstone clasts have angular to subrounded in shape, bedding is planar, and dune structures are common. Angular to subangular fragments of medium to dark gray basalt are found near the center. The age of the basalt is 0.59 ± 0.03 Ma based on K/Ar dating. The maar deposits have not been dated yet.
Silamuk (MO-1)	A parasitic cone found at an elevation of 1200 m a.s.l. in the eastern part of Crater-II. Its lava consists of trachyandesites with phenocrysts of alkali feldspar, plagioclase, and orthopyroxene in a fine-grained groundmass with trachytic texture. The age based on K/Ar dating is 0.69 ± 0.03 Ma.
Argojembangan (MP-2)	A cinder cone located on the southern flank of Muria at an elevation of 1400 m a.s.l. The lava from this vent has phenocrysts set in an aphanitic groundmass. The age is unknown, but it may be similar to the Silamuk deposits of 0.69 ± 0.03 Ma.
Mt. Joglo Lava Dome (MP-3)	This lava dome is located on the southwestern side of Muria peak at an elevation of about 1350 m a.s.l. The dome consists of lavas with columnar jointing in its lower part, and sheeted joints in its upper part. The lavas have a gray, porphyritic texture with small phenocrysts of feldspar and pyroxene set up in an aphanitic groundmass. The lava dome has not been dated but is thought to correspond to Muria Crater-IV, having an age of 0.5 ± 0.2 Ma.
Alas Krasak (MP-4)	A parasitic cone located at an elevation of 1150–1200 m a.s.l. It produces leucite tephrite lavas with columnar jointing in its lower part, and sheeted joints in its upper part. The rock is porphyritic with phenocrysts of leucite, alkali feldspar, plagioclase, and augite. Two K/Ar age determinations gave 0.34 ± 0.02 and 0.32 ± 0.07 Ma.
Sutarengga Lava Dome (M2K2)	A lava dome located inside Muria Crater-II at an elevation of 1500 m a.s.l. The lavas are gray trachyandesites with phenocrysts of plagioclase set up in a holocrystalline groundmass. Ar/Ar whole-rock dating indicates that the eruption products are 0.67 ± 0.034 Ma in age.
Rahtawu Lava Dome (M3K)	A lava dome located in Crater-III of Muria on northwestern side of the peak, associated with a NE-trending fault at an elevation of 1400 m a.s.l. Tephrite with phenocrysts of augite, biotite, and plagioclase set in a holocrystalline groundmass. The age based on K/Ar whole-rock dating is 0.69 ± 0.03 Ma.

Table 1 (Continued).

Name of vent	Geological features
Peak Crater Lava Dome IVa (M4K1)	Located at the summit of Muria, within Crater-IV, 1550–1600 m a.s.l. This crater is located at the intersection of NE and NW trending faults. Lithologically, it consists of trachyandesite with phenocrysts of augite, plagioclase, and alkali feldspar set in a holocrystalline groundmass. K/Ar dating of the lava gave an age of 0.34 ± 0.02 Ma.
Peak Crater Lava Dome IVb (M4K2)	Located on the eastern side of Muria, within Crater-IV. The elevation is 1550 m a.s.l. This lava dome occurs at the same fault intersection as IVa. It consists of porphyritic trachyandesite, with phenocrysts of augite, plagioclase, and alkali feldspar set in a holocrystalline groundmass. K/Ar dating gave an age of 0.32 ± 0.07 Ma.
Genuk Crater-II (G2Pf1)	A crater located on the southeastern side of the summit. Estimated size is 2.5×1 km and the elevation is 650 m a.s.l. A lava dome occupies the center of the crater. Pyroclastic flows on the west slope of Genuk are assigned to this crater.
Genuk Crater-III	A crater located north of Crater-II. Dimensions are about 1.5 km wide and 1 km long. Elevation is ± 650 m a.s.l.
Genuk Crater-IV	A crater located north of Crater-II. Dimensions are about 1.5 km wide and 1 km long. Elevation is ± 650 m a.s.l.
Genuk Crater-V	The smallest and youngest crater located at the summit of Genuk, within Crater-V, at an elevation of 700 m a.s.l. The crater diameter is 0.5 km.
Telon (G2K)	Located within Genuk Crater-II at an elevation of 650 m a.s.l. The dome is associated with pyroclastic flows containing blocks of pyroxene andesite lava. The topography can be distinguished easily from weaker materials surrounding the dome. Lavas of this dome are trachyandesites with phenocrysts of augite, alkaline feldspar and calcite in a holocrystalline groundmass. Also contains calcite. The age is unknown.
Blumbang (G3K)	Lava dome located in the Crater-III of Genuk with an elevation of 650 m a.s.l. It is characterized by andesite of porphyritic texture, zoned alkaline feldspar and calcite set in the holocrystalline groundmass.
Wangkong-G4K1 and -G4K2.	East and west lava domes in Crater-IV of Genuk west of the peak. The elevation is approximately 700 m a.s.l. The domes consist of trachyandesite with phenocrysts of biotite, aegirine–augite, plagioclase, and a few olivines set in a holocrystalline groundmass. The age of the dome is unknown, but stratigraphic relations indicate that it can be correlated with eruption products.
Peak-1 (G5K)	Located inside Crater-V of Genuk; forms the highest peak at 750 m a.s.l. A dome of basanite lava having a diabasic texture with phenocrysts of leucite, a few olivines, plagioclase, and aegirine–augite in an inter-granular groundmass. K/Ar dating indicates that the age of the dome is 0.69 ± 0.03 Ma.
Muria Crater (M-0)	This crater is believed to be the oldest on Muria Volcano. The crater is now invisible because later craters have destroyed it.
Genuk Crater-I	The oldest crater located on the southernmost side of Genuk summit at an elevation of 650 m a.s.l. The crater has not been destroyed by the series of younger craters. The group II eruption products of this crater can still be recognized as basalt that flowed toward the western part of the volcano.
Bondo (ML-1)	Located in Bondo village, about 35 km west of the summit Muria. The area where the outcrop is to be found is relatively flat. The outcrop consists of heavily weathered pyroxene andesite. Whole-rock dating by Ar/Ar indicates that the lava flow is 0.637 ± 0.03 Ma. The exact source of the lava is undetermined.
Pligen River (ML-2 and ML-2x)	Both located in the Pligen River, these outcrops are autoclastic basalt lavas associated with fluvial and volcanic breccia deposits. The outcrops have a porphyritic texture with augite and plagioclase as the main phenocrysts set in a groundmass of plagioclase microlites and glass. The absolute age of the outcrops is unknown.
Banjaran River (ML-3)	The outcrop is located at Kedung Dowo Dam in the Banjaran River. A large outcrop of volcanic breccia is located on the bottom of the river. The breccia appears to be composed in the lower part of heterogeneous, angular blocks in a matrix of sand. In the upper part, large, flattened lenses of lava are to be found. The lava is composed of leucite basanite and has rubbly brecciated margins. The main product is an autoclastic pyroxene andesitic lava associated with lahars, volcanic breccias, and fluvial deposits of the Banjaran River. The age based on Ar/Ar dating is 0.75 ± 0.2 Ma, making it the oldest lava flow found near the site. The source is yet to be determined.

Table 1 (Continued).

Name of vent	Geological features
Mlonggo (ML-4)	An outcrop of sheeted, autoclastic lava located in the lower part of Mlongo River. It is very similar to the outcrops in the Krasak and Pligen rivers. The source and absolute age of the lava are unknown.
Bangsri circular depression	A circular depression identified by SAR. Geological inspection on the ground indicated that the depression contains five different lavas and one pyroclastic-flow deposit. The absolute age has not been determined. It is uncertain whether the lavas and pyroclastic flow are associated with the depression or came from another source.

magnitude is in the range of 3–4. Unfortunately, the records from these sources were never combined into a single data set for all of Muria Peninsula. The epicenter determinations are not very reliable and hypocenters, focal mechanisms, and stress drop data are missing.

Because of these deficiencies, the macro- and microseismicity data were of little use for defining seismogenic structures. Only the Pati earthquake is shown in Fig. 5. This means that the location and characterization of the seismogenic sources needed for the assessment of seismic hazards at the Muria site had to be based mainly on neotectonic (geologic, geomorphological and geophysical) data.

Before discussing the manner in which this was done it will be helpful to define two terms that embody basic concepts used in assessing seismogenic potential.

Capable faults are those active faults on which earthquakes cause a displacement of the topographic surface. They are typically of magnitude greater than 6 or 6.5. Faults are considered capable when they show evidence of past movements of a recurrent nature in a period of time in which it is reasonable to infer that further movement could occur during the lifetime of the nuclear power plant. They are recognizable from geomorphic evidence or evidence of offset in very recent strata, which, in a geological environment like that of Java, would be the Late Quaternary.

Rupture length is the length of the capable fault that can be ruptured by an earthquake of a given size. Therefore, it represents only a part of the ‘total length’ of the fault. For tectonic faults the rupture length can be estimated as a percentage of

the total length or by use of segmentation criteria based on displacement data (historical, paleoseismological, geomorphological, etc.).

These terms and the concepts on which they are based are fully applicable to purely tectonic structures, but application to volcano-tectonic structures requires a significant amount of professional judgment.

5.2. Faulting of purely tectonic nature: Rembang Depression and its offshore extension

Signs of faulting were detected in the analyses of seismic reflection data in the northern part of the Java Sea, but these faults seemed to have the same characteristics as the ones in the near regional area. (For details, see Section 5.4.)

The only significant regional structures for seismic hazard assessment at the Muria site are the fault systems that border the Rembang Depression to the north and south and their offshore extension: AF-1 to AF-5 in Fig. 5.

Signs of faulting were detected in the analyses of seismic reflection data for the northern part of the Java Sea, but these faults seem to have the same characteristics as the ones in the near regional area.

All surveys indicated that AF-1, AF-2, AF-3, and AF-4 could be capable (although with different degrees of confidence), but there was serious disagreement among the investigators on certain factors that characterize them, such as fault lengths, most recent activity, and style of deformation.

The Rembang Depression is referred to as a pull-apart basin, formed by two fault systems. There was a general consensus among the inves-

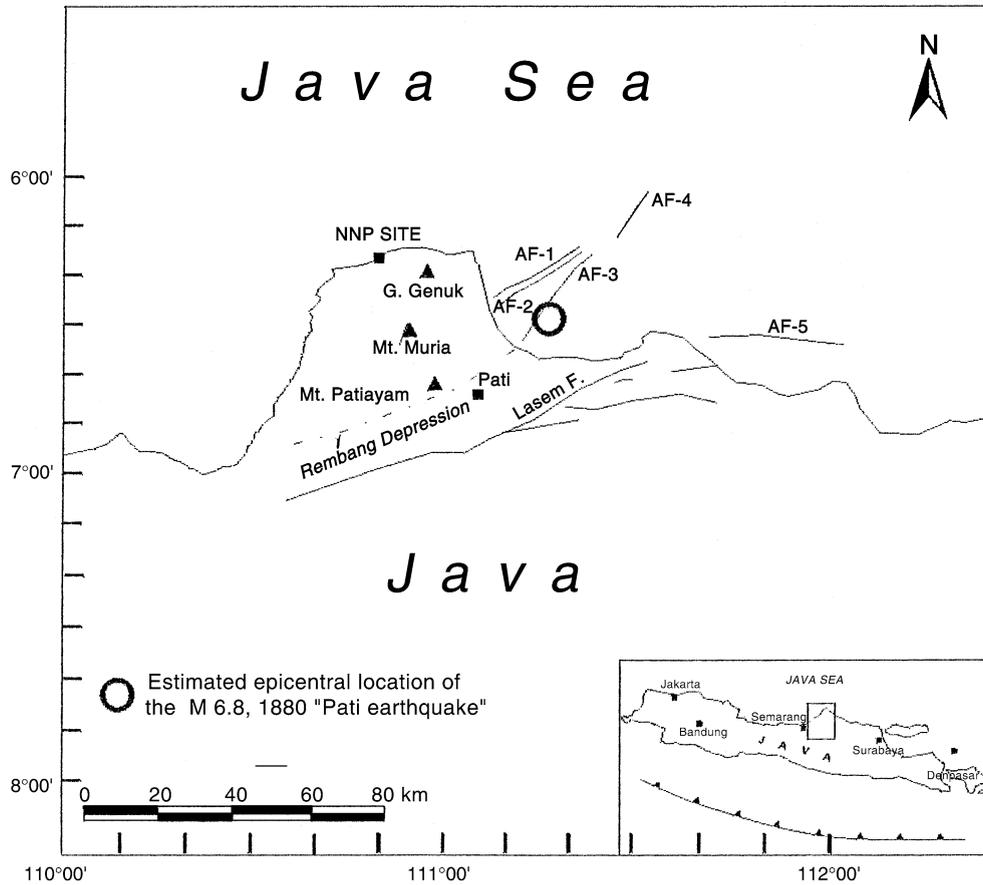


Fig. 5. Volcanic and tectonic features in the vicinity of the proposed nuclear power plant.

tigators that both fault systems are clearly identified by geomorphological and geophysical data and that they are capable. These two fault systems are the most important ones for the determination of the SL-2 level earthquake. (For more details, see [Mallard et al., 1991](#) and [Serva, 2001](#)).

Regarding the onshore–offshore fault correlations, AF-1 and AF-2 approach the shoreline along the east coast of the Muria Peninsula. Onshore geological studies have not found any indication of active faulting corresponding to the southwestward extension of these faults. If these data are confirmed it means that these two faults are not capable, because they are preceded or accompanied by volcanic activity, and only AF-3/AF-4 could represent the offshore extension of the potential fault controlling the northern edge of the Rembang Depression. However, further in-

vestigation of this area should include an analysis of onshore seismic profiling data.

As explained above, owing to a lack of structural and seismological data for the area the information on the kinematics of reported fault systems was equivocal. For example, geodynamic considerations related to the north–northeast subduction suggest that the Rembang Depression could be the result of either a left lateral transpressive or a right lateral transverse fault system.

The evaluation of the maximum potential magnitude for the structures bordering the Rembang Depression and the AF-1/A-5 offshore faults can be derived according to the equation ([Mohammadioun and Serva, 2001](#)):

$$M_s = 2 \log L + 1.33 \log \Delta\sigma + 1.66 \quad (5)$$

where M_s is the surface-wave magnitude, L is the

fault rupture length (km) and $\Delta\sigma$ is the stress drop released by the earthquake (in bars) that depends on fault width and kinematics (reverse, strike-slip and normal mechanisms).

Unfortunately, because of the lack of information, values for the rupture length, stress drop and kinematics of faults must be assumed. Stress drop data are computed using fault zone width according to the formula derived by [Mohammadioun and Serva \(2001\)](#):

$$\Delta\sigma R = 4.8 \times W^{1.6} \quad (6)$$

$$\Delta\sigma SS = 8.9 \times W^{0.8} \quad (7)$$

$$\Delta\sigma N = 10.6 \times W^{0.5} \quad (8)$$

where: $\Delta\sigma R$, $\Delta\sigma SS$, and $\Delta\sigma N$ are the stress (in bars) released for reverse, strike-slip and normal fault mechanism, respectively; and W is the fault width (km).

Maximum potential surface-wave magnitudes, M_s , associated with these structures assuming W ranging between 5 and 20 km ([Fig. 5](#)), L ranging between 30 and 50, and reverse, strike-slip and normal kinematics are computed in [Table 2](#). This table reports the parametric modelling used to assess the maximum magnitude of these seismogenic structures.

The $M=6.8$ Pati earthquake that was assumed to have occurred along AF-3, is consistent with a 30-km rupture length for that fault assuming strike-slip or normal kinematics. This good agreement between computed and the observed extent of the AF-3 fault, is mentioned only for the sake of illustration, and in our judgment the lack of a consistent seismic database and structural uncertainties make these results unreliable.

The minimum distance from the site of the proposed nuclear plant to the northern fault is of the order of 35 km, if we consider faults AF-1 and AF-2 as part of this structure or about 40–45 km if they are not. For the Lasem fault the minimum distance is about 50–55 km.

It is important to note that no strong earthquakes have been recorded in the onshore area of these faults. This may be due to the incomplete nature of the seismic catalogue, but it could also be due to a different seismic behavior in the vicinity of the volcanic centers. The weaker rheological conditions of rocks near the Muria complex could prevent an accumulation of strain energy. An example of such seismic behavior is at the Iblean–Malta fault escarpment (Sicily, Italy), where these faults approach the Etna volcanic system. The maximum potential magnitude of this fault escarpment, in the Ionian Sea, has been assessed at $M_s=7.2$ on the basis of fault characterization data confirmed by the historical earthquakes of AD 1169 and 1693 ([Monaco and Tortorici, 2000](#)). In the inland prolongation of this structure (i.e. Timpe normal fault system, southeast of Etna) the maximum magnitudes are below $M_s=5$ ([Azzaro et al., 2000](#); [Mohammadioun and Serva, 2001](#)).

If this is the case, the distance from these two structures to the proposed site should be reassessed for the Lasem fault, because the distance from the northern fault does not change significantly.

5.3. Volcano-tectonic structures in the near-regional area

A prominent north–south structure crosses Mu-

Table 2

Modelling of maximum potential surface-wave magnitude related to AF1/AF5 offshore faults and structure associated to the Rembang Depression

Mechanism	Reverse faults			Strike-slip faults			Normal faults		
	5	10	20	5	10	20	5	10	20
Fault width (km)	5	10	20	5	10	20	5	10	20
Stress drop (bars)	63	191	579	32	56	98	24	34	47
Fault length (30 km)	7.0	7.6	8.3	6.6	6.9	7.3	6.4	6.6	6.8
Fault length (40 km)	7.3	7.9	8.5	6.9	7.2	7.5	6.7	6.9	7.1
Fault length (50 km)	7.5	8.1	8.7	7.1	7.4	7.7	6.9	7.1	7.3

Modelling has been derived according to the equations reported in [Mohammadioun and Serva, 2001](#).

ria Volcano and connects it with the Patayayam Dome and Genuk Volcano (Figs. 1 and 4). This structure was recognized, even in the earliest studies, because the upper part of Muria is elongated in this direction and Genuk and Patayayam are on the northern and southern extension of the same alignment. However, the lack of on-land geological, geophysical or geomorphological evidence, as well as the fact that no sign of a possible offshore prolongation of this structure was identified in the high resolution seismic reflection surveys, lead at the conclusion that this feature may not exist, at least, as a through-going tectonic structure. Furthermore, the available evidence from diffuse seismicity and the lack of geological evidence suggest that this structure is not associated with deep, through-going crustal faults of high seismogenic potential. Similar structures that have been postulated elsewhere on Muria Peninsula may or may not be related to the volcanic centers. Other volcanological phenomena, compatible with the present state of the Muria Volcano, can produce earthquakes and despite their relatively low seismogenic potential, these events should be included in the seismic hazard assessment and integrated with the evaluation of volcanic hazard.

A general review of the maximum magnitude related to volcano-tectonic structures is reported in Hackett et al. (1996), Zobin (2001), and references therein. A magnitude 5 event located 5 km below the proposed site would be a reasonable earthquake to take as representative of the seismic hazard posed by the volcano-tectonic features. This conclusion is based on analogies with similar volcanoes in comparable tectonic settings. The best examples are probably the potassic back-arc volcanoes of the Alban Hills in central Italy. The Alban hills are built on a sedimentary substratum, consisting mainly of marine sands, silts, and sandy clays similar to those under Muria Peninsula. Activity began less than 0.6 million years ago and no evidence for eruptions has been found in archaeological and historical records (Vologio et al., 1994). At present the Alban Hills area is affected by frequent earthquakes that often occur as cascading swarms, especially on the western side of the volcano. Focal mechanisms are mainly

normal faulting with a subordinate strike-slip component. Hypocenters are generally confined to depths of 3–7 km. Several records of seismic activity can be found in historical accounts from Roman times. The historical catalogue, considered complete at intensity $I > V$ degree MCS (Mercalli–Cancani–Sieberg scale, essentially the same as the Modified Mercalli scale) later than the eighteenth century, reports events with a maximum intensity, I , of VIII degrees MCS in 1806, 1829, 1899 and 1927 (for the latter a magnitude $M = 4.5$ was computed). In the last two decades (1980–2000), when good instrumental measurements were available, the maximum intensities recorded reached VI degrees MCS, corresponding to a magnitude of 3.9. Taking into account the time interval involved in these records and the geographic and sociocultural conditions of the Alban Hills since Roman times it is quite possible that in the last 2000 years the earthquakes in this region never exceeded magnitude 4.5 or 5 and we can reasonably conclude that this is a reasonable maximum earthquake to assume for the Muria volcanic complex.

5.4. Background (random or floating) earthquakes

The background earthquake represents the maximum size and least favorable hypocenter location of an event that, considering the tectonic setting, can occur in the vicinity of the proposed site. As mentioned earlier, a volcano-tectonic event can also occur at the site, since it is located within the Muria structure. Therefore it could represent a background earthquake.

In the offshore region, seismic reflection data show horizontal layering of the whole Mesozoic–Cenozoic and Quaternary sequence in the Java Sea and no significant signs of faulting were revealed in the northern part of Muria Peninsula. Structures related to potential faulting have been mapped at a scale of 1:50 000 by different consulting companies, but the documentation and evaluation of the data are incomplete and appear to contain errors. In any case, the accuracy of these maps was questionable and the detection, characterization, and dating of the faulting are unclear. Finally, there was a consensus that

these were thought to be growth faults none of which has been identified as capable. For that reason, they have no significant seismogenic consequence, i.e. their seismogenic potential is smaller than that associated with the volcano-tectonic structures. From this we conclude that it is a conservative assumption to take earthquakes associated with the volcanic structures as a background earthquake consistent with the tectonic structures found in the offshore area, and also with the diffuse seismicity in the near region of the site derived from the macro- and microseismicity data given above.

5.5. Discussion of seismic hazards

The proposed seismotectonic model is consistent with the present state of knowledge, but it needs support and confirmation by additional data.

Deep earthquakes related to subduction of the Indian Plate beneath Java seem to have no significant effects at the site. Data from the international database show a maximum magnitude between 6.0 and 6.5 at depth of about 140 km. For this reason, they are not included in the calculations of the seismic hazard.

Regarding the near-source earthquake, there was a consensus among the various investigators that the area offshore and west of Muria includes no faults that can be identified as capable, and that the observed structures have no seismogenic significance. In other words, their seismogenic potential is less than that assumed for a volcano-tectonic earthquake. The nature of the volcano-tectonic earthquake assumed here is based on analogies with those associated with the Alban Hills volcano in Italy. The 'back-ground' earthquake proposed for design purposes is based on the same analysis of volcano-tectonic events. This earthquake includes the diffuse seismicity of the region around the site on Muria Peninsula and the seismic potential of growth faults in the area offshore.

The most likely source of far field earthquakes is along the faults on the northern and southern borders of the Rembang Depression.

Parametric modelling of earthquake magni-

tudes has been proposed as well as locations that should be assumed in the design of structures at the proposed site. The 'design earthquakes' must take into account the attenuation from the sources to the site and the geotechnical properties of foundation materials.

As explained above, the possibility of surface faulting at the site can be reasonably excluded, but additional confirmatory data are needed.

Two important issues are still open: the bearing capacity of foundation sediments and the feasibility of a dewatering system during construction and operation of the plant under static and dynamic (earthquake) conditions. In this regard, it is important to recall that: (1) the geotechnical properties of the sediments at the site are very poor because they are very weathered to depths well below the proposed excavation, and (2) the permeability of these volcanic terrains is very high, and the groundwater level is at sea level near the coastline.

The original plan was to construct a nuclear plant using safety standards developed for Japan. The criteria included a back-ground earthquake of magnitude 6.5 located 10 km from the site. This criterion has been used for nuclear power plant sites in Japan where the foundation rocks are no younger than Tertiary. The use of Japanese criteria at the Muria Peninsula site could be inappropriate, and application would make the stability of the foundation questionable. Similarly, the effectiveness of the dewatering system would be uncertain. On the other hand, the preliminary studies seem to show a lower seismic hazard at this site, and the seismic criteria for defining the feasibility of the site may be less severe.

6. Summary and conclusions

The geological investigation has shown that the volcanic complex on Muria Peninsula must be considered capable of future volcanic and seismic activity. Evidence of recent volcanic eruptions is manifested in explosion craters on the flanks of Muria Volcano. Judging from the records of other volcanoes of this type, the period that has elapsed since these craters were formed 2000–5000 years

ago is less than the intervals between eruptions of many long-dormant volcanoes of similar form and composition. Further evidence that an active magmatic body still resides beneath the area is found in the composition of gases emitted near the base of the volcano and in boreholes near the site of the proposed plant.

The site lies within the screening distances for at least four possible types of events: (1) fallout of pyroclastic material, (2) pyroclastic flows and surges, (3) debris flows, lahars, and floods, and (4) opening of new vents. Adequate safeguards for pyroclastic fallout can be incorporated into the design of the plant, but the other possible hazards are more serious.

The studies also showed that although additional confirmatory data are needed, there appear to be no capable faults at or near the site of the proposed nuclear plant. Our seismotectonic model for assessing the seismic hazards of the area indicates that the hazards are less than the criteria used for construction of nuclear power plants in Japan. On the other hand, taking into account the poor geotechnical properties of the foundation materials and the high groundwater level, the assessed seismogenic potential could prejudice the feasibility of the plant.

Under these conditions, a probabilistic analysis of the risk associated with each of these phenomena would normally be carried out using the methods outlined by Hill et al. (1998) and Connor et al. (2001).

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