Provisional Safety Standards Series No. 1

IAEA-PSS--01

Volcanoes and associated topics in relation to nuclear power plant siting

July 1997

INTERNATIONAL ATOMIC ENERGY AGENCY

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FOREWORD

This report is intended to provide information and draft guidance on a subject which is still undergoing development at both the international and national levels, namely the siting of nuclear power plants in volcanic areas. Users of the report are encouraged to provide feedback on the text in order to assist the IAEA in the compilation of a future Safety Standards Series publication.

EDITORIAL NOTE

CONTENTS

1. INTRODUCTION

BACKGROUND

101. This report provides guidelines and recommends procedures to adopt in the consideration of volcanoes and associated topics for nuclear power plant siting. The Code on the Safety of Nuclear Power Plants: Siting (50-C-S, Rev. 1) indicates that historical data concerning phenomena that have potential to produce adverse effects on the safety of the nuclear power plant, such as volcanism, shall be collected and evaluated. If the potential is confirmed, design bases should be derived accordingly (see para. 440 of the Code).

102. Engineering solutions are available to mitigate some potential effects of external events through design. However, when such solutions either are not practicable or cannot be demonstrated as being adequate for mitigation of the effects of volcanic phenomena, it may be prudent to select an alternative site.

103. In the various phases of site survey leading to the selection of a site, particular attention should be paid to two categories of features related to volcanoes:

(1) Features that can have direct influence on the acceptability of the site.
(2) Features that can influence the severity of the effects of the volcanic activity on the plant, i.e. the design basis parameters.

Information related to investigations during a site survey may be found in Safety Series No. 50-SG-S9, a Safety Guide.

OBJECTIVE

104. The main purpose of this report is to provide draft guidance on the criteria and methods for the evaluation of a site for a nuclear power plant with respect to the potential effects of volcanic activity which may jeopardize its safety and to elicit feedback from Member States. Different types of phenomena associated with volcanism are discussed in terms of their influence on site acceptability and on derivation of design basis parameters.

SCOPE

105. This report was developed for application to new nuclear power plant sites. It does not address the issue of the re-evaluation of existing nuclear power sites to the potential effects of volcanic activity, although it contains general information and criteria useful for this purpose.

106. The guidelines and procedures discussed in this report can appropriately be used as the basis for the safe siting and design of nuclear power plants in different volcanic environments.

STRUCTURE

107. In this report, the description of the phenomena associated with volcanism and the collection of required data and information are separated from the criteria for hazard assessment. Thus Section 2 gives the non-specialist a general description of the different types

of volcanic phenomena and Section 4 provides indication on the acquisition of the database. Section 3 outlines the general requirements to be fulfilled during site selection and evaluation. Sections 5, 6 and 7 provide guidance to perform the hazard assessment and to derive the design basis parameters. Finally, Section 8 deals with monitoring systems. As general information for the non-specialist, Annex I provides the major divisions of geological time. With the same spirit, and recognizing that a complete consensus has not been reached in the scientific community on the use and meaning of some terms, a glossary of volcanological definitions is given in Annex II, applicable only to the use of this report. Finally, Annex III provides an example of a classification of volcanoes that may be used for capability assessment, as required in Section 5.

108. Guidance related to some of the subjects covered in this report can be found in Safety Guides Nos 50-SG-S1 (Rev. 1), 50-SG-S5, 50-SG-S8 and 50-SG-S10A.

2. TYPES OF VOLCANIC PHENOMENA

201. This section briefly describes the main types of volcanic phenomena that may affect a site. It provides an indication of the order of magnitude of critical parameters for each phenomenon such as density, velocity, temperature and areal distribution. The quantification of these parameters requires detailed study of the area as described in Section 4. The manifestations of volcanic activity that may affect the site can be listed as follows [1–3]:

(1) ballistic projectiles
(2) fallout of pyroclastic material (ash, pumice, scoria, etc.)
(3) pyroclastic flows and pyroclastic surges
(4) air shocks and lightning
(5) lava flows
(6) debris avalanches, landslides and slope failures
(7) debris flows, lahars and floods
(8) volcanic gases
(9) ground deformation
(10) earthquakes
(11) tsunamis
(12) geothermal anomalies
(13) ground water anomalies
(14) opening of new vents.

Ballistic projectiles

202. Ejection of ballistic projectiles such as blocks, bombs and other solid fragments is caused by explosions occurring within craters, domes, or vents. The solid objects are propelled by high pressure gas and follow ballistic trajectories. The speeds of the projectiles can be more than 300 m/s and the maximum horizontal distances they may travel to the impact point can exceed 5 km from the origin. When the size of projectiles is sufficiently small, the friction of air decelerates them enough to affect their trajectory. Typically, projectiles larger than 1 m in diameter would not be significantly affected by the drag forces.

203. This phenomenon is common to all eruptions but is most frequently observed in explosions from domes, vulcanian eruptions, phreatic or phreatomagmatic explosions. The impact energy of a single projectile may reach 1 Joule. If projectiles at high temperatures fall on vegetation, houses or other flammable structures, they may start fires.

204. Hazard zones associated with ballistic projectiles are normally mapped as concentric circles around existing vents. Radii of hazard zones are determined from the distribution of ballistic projectiles deposited during past eruptive episodes and using probabilistic estimates of eruption energies [4].

Fallout of pyroclastic material

205. The fall and deposition of pyroclastic material such as ash, pumice and scoria occur when these particles are propelled by an explosive eruption to an altitude at which they can be carried by wind. On falling they normally reach a constant velocity (so-called terminal velocity), which is determined by the size, shape and density of the falling particle. Their distribution is governed by the direction and strength of prevailing winds and height of the ash column.

206. If the ashfall is thick, it may cause serious damage to transportation, agriculture, forests and other social and economic activities. By loading the roofs of buildings, ash accumulation may cause collapse, particularly when the ash becomes soaked by rain. Ash particles drifting in the air sometimes obstruct air traffic by sandblasting the exterior of aircraft and damaging and even stalling jet engines [5].

207. The most voluminous pyroclastic falls are produced by Plinian type eruptions in which large amounts of high-temperature pyroclastic material is thrust upward from the crater by a high-velocity gas jet [6–8]. At a certain height, admixture and heating of air creates a column of rapidly expanding and ascending gas and suspended solid particles which may reach the stratosphere. Such activity usually forms a mushroom shaped eruption column that may be carried by atmospheric currents at high altitude. A significant fall deposit from a typical Plinian eruption can extend several hundred kilometres or more from the source and may be tens of metres thick near the vent. A Plinian eruption normally lasts only hours or days but it produces a very large amount (up to 100 km^3) of pyroclastic fall deposits [9].

208. Hazards due to pyroclastic falls are usually determined by mapping past fall deposits, consideration of current wind patterns, and often by computer simulation [10–15]. In some areas seasonal wind direction diagrams can be developed.

Pyroclastic flows and pyroclastic surges

209. Pyroclastic flows are high-temperature mixtures of rock fragments, volcanic gases and air that flow down the slope at high speeds [16–18]. Flow velocities reach 10 to 100 m/s making evacuation impossible once a pyroclastic flow has begun. The temperature can be close to that of the original magma (around 1000°C in many cases) or near ambient temperatures depending on the degree of mixing with air. Downslope movement of the pyroclastic flow is driven primarily by gravity. The high mobility of the flow indicates that internal friction is very small. Pyroclastic flows may have sufficient momentum to deviate from drainage lines and to pass over topographic obstacles.

210. Many pyroclastic flows consist of two different parts, although the transition between the two may be gradual. The majority of the moving solid material is concentrated at the bottom part of the flow and the top is a more dilute mixture of ash and gas that rises like a thick dust cloud. The lower, dense part of the pyroclastic flow may have a bulk density of 0.1–0.5 t/m^3; the upper dilute cloud has a bulk density close to 0.001 t/m^3. This dilute part often separates from the denser part and travels considerable distances downwind.

211. The volume of solid materials transported by a pyroclastic flow may range from less than 10^5 m^3 to more than 10^{11} m^3, depending on the mode of generation and emplacement. Most large scale pyroclastic flows are generated by wholesale vesiculation of felsic magma stored in a shallow magma chamber. Large amounts of magma are progressively fragmented and ejected from the vent because of the rapid formation and expansion of the bubbles in the ascending magma. Such eruptions may lead to the collapse of calderas. Thick, hot deposits may extend more than 200 km from the vent and cover an area of more than 10^4 km^2. Smaller pyroclastic flows may be formed by the partial collapse of growing lava domes or thick, blocky lava flows. Explosions of gas from domes cause vertical ejections of pyroclastic material, part of which may generate pyroclastic flows when it falls back to the surface. Small scale pyroclastic flows have been witnessed on the slopes of large volcanoes but there are no historical accounts of very large flows of the kind that have erupted and produced calderas in the past. Owing to their great mass, high temperatures, velocity, and great

mobility, pyroclastic flows present serious hazards, including burial, incineration, asphyxiation and impact. Secondary hazards derive from large amounts of melt water from snow capped volcanoes generating lahars and floods.

212. Pyroclastic surges are turbulent, dilute gas-solid suspensions that flow over the ground surface at high velocities with less regard to topography than pyroclastic flows. They can be divided into two types, hot and cold. Hot pyroclastic surges, also known as ground surges, are generated by many of the same processes that form pyroclastic flows and often over-ride or precede pyroclastic flows. Cold pyroclastic surges, also known as base surges, originate from hydromagmatic explosions in which shallow ground water or surface water interacts with magma. They typically contain water and/or steam and have temperatures at or below the boiling point of water. Base surges are generally restricted to a radius of 16 km from the vent. Pyroclastic surges pose a variety of hazards including destruction by ash-laden clouds, impact by rock fragments, and burial. Hot pyroclastic surges present several additional hazards including incineration, toxic gases, and asphyxiation.

213. Hazards associated with pyroclastic flows and surges are evaluated by mapping past deposits, studying their physical volcanology and estimating their temperature of emplacement. Analysis of topography and drainage patterns and computer simulation are also used to estimate hazards associated with these phenomena [19].

Air shocks and lightning

214. Explosive eruption of a volcano can generate supersonic shock waves powerful enough to break windows at distances of several kilometers. They are accompanied by projection of bombs and blocks as discussed in the previous section but the radius of the shock wave effects may be greater than that of the projected material.

215. Lightning often accompanies volcanic eruptions. Lightning results from charge differences between the erupting column of ash and the atmosphere. In some cases, lightning and high static charges occur up to several kilometers from the erupting volcano.

Lava flows

216. Flows of lava are driven by gravity and follow the drainage lines of the topography [20]. They behave like viscous fluids, usually with a semi-solid crust on the surface. The morphology and velocity of lava flows depend on the eruption rate, temperature, composition, vent geometry and topography. Common morphologic types of lava flows include pahohoe, aa, and block lava flows. These different morphologies indicate different magma viscosities and sometimes different effusion rates. Their length can range from a few metres to tens of kilometres and their width from less than one metre to more than 100 m. The temperatures of basaltic lavas may be as high as 1200°C; dacitic and rhyolitic lavas may be 1000°C or less. Unusual lavas such as the carbonates erupted at Ol Doinyo Lengai (Tanzania) may have temperatures as low as 400°C.

217. The speed of a lava flow is normally low, but some silica-poor and/or high-temperature lava flows may reach speeds of more than 10 m/s on steep slopes. The lava flows of Nyiragongo (1977, Zaire) and of Ol Doinyo Lengai (Tanzania) volcanoes reportedly reached velocities greater than 10 m/s. However, the advance of the front of even the most fluid basaltic lava flows is normally much slower, usually a few m/s or less. More felsic lava flows such as andesitic, dacitic and rhyolitic, advance more slowly, less than 100 m/day on

gentle slopes. When the viscosity and yield strength of felsic lava are high, the lava may form a lava dome with a height to diameter ratio much larger than that of lava flows. Lava domes may reach heights of more than 100 m and have widths of several hundred metres.

218. Hazards associated with lava flows are usually estimated by mapping the distribution of past lava flows, mapping current drainage patterns and related topographic features that would control lava flows, and mapping vents from which lava flows could erupt. Computer simulation of lava flows has been used to estimate hazards [21, 22].

Debris avalanches, landslides and slope failures

219. Most volcanic edifices are steep-sided and may therefore become unstable as a result of erosion or deformation. Partial or complete failure of the slopes often produces debris avalanches, which are high-speed turbulent flows of rock fragments and entrapped air [23, 24]. The mode of movement of debris avalanches is therefore similar to that of pyroclastic flows in that both phenomena are downslope flows of mixtures accelerated by gravity. Although not as large as debris avalanches, detachment and collapse of unstable slopes of the volcanic edifice may lead to landslides and other types of sudden slope failures, triggered by an earthquake or heavy rainfall.

220. The temperatures of most debris avalanches are much lower than those of the pyroclastic flows and range between ambient temperature to a few hundred degrees Celsius depending on the original temperature of the rocks. Elevated temperatures of deposition can be determined from the presence of a significant fraction of juvenile material in the deposit, the presence of charred wood or using paleomagnetic methods [25, 26]. The volume of collapse may reach more than 10 km^3 and the speed of the resulting flow may exceed 100 m/s.

221. A large collapse may leave a horse shoe-shaped scarp on the upper part of the slope. Deposits may reach thicknesses of several tens of metres and extend tens of kilometres from their origin. The damage caused by a debris avalanche is mainly by physical impact and burial and the devastation in the central part of the flow can be total.

222. Hazards associated with volcanic debris avalanches and related phenomena are estimated by mapping the distribution of these deposits and related facies, such as lahars, in the region of the volcano, and by identifying morphological features which indicate that large scale collapse has occurred in the past. Topography, structural studies of the volcano, and computer analysis of simulated volcano collapse events assist in the estimation of risk at a particular site.

Debris flows, lahars and floods

223. Mixtures of solid volcanic material and water, as well as other rocks, soil and vegetation, frequently form torrents which flow down valleys and river courses whenever abundant surface water is available after heavy rainfall [27, 28]. These are called volcanic debris flows and lahars. They range from flows containing many large boulders cascading down steep slopes to muddy currents sweeping over wide areas at the foot of the volcano. Debris flows and lahars grade into flood streams, heavily loaded with suspended sand and clay particles.

224. Eruptions of mixtures of solid fragments and water directly from active vents or craters are not common but may result from eruptions through abundant meteoric water. These

eruptions may also be triggered by torrential rains, melting ice and snow, landslides, breaching of crater lakes, and other conditions where large amounts of loose unconsolidated material are present on volcanic slopes.

225. Volcanic debris flows and lahars share similar features with their non-volcanic equivalents. Their dynamic behaviour is dictated mainly by the nature and proportions of material, topography, their dimensions, and weather. Although flow velocities are slower than those of pyroclastic flows, large debris flows and lahars may travel 50 km or more and have volumes of more than 10^7 m^3. Physical damage caused by volcanic debris flows and lahars may also be comparable to that of their non-volcanic equivalents [29].

226. Floods can be triggered by landslides, pyroclastic flows, debris avalanches, debris flows and lahars that can be generated near the volcanic centre by melting ice or snow or on more distant slopes that have become unstable as a result of accelerated erosion. Depending on the initial condition of the water system, sudden injection of volcanic material may lead to large-scale flooding of the lower river course. Silting and damming by the large amount of sediments transported and deposited by these floods can pose a serious threat to river facilities and water supplies.

227. Mapping of lahar deposits provides one means of evaluating this hazard. However, deposits from extremely destructive lahars are often minimal and may be missed in the geologic record. Lahar hazards are often evaluated by (i) identifying potential source regions for lahars, including crater lakes, summit glaciers, and seasonally high rainfall; and, (ii) identifying drainage patterns likely to contain lahars and to transport these flows great distances. In the past, geologic mapping of these hazard zones has been highly successful in forecasting the areas impacted by lahars [30, 31].

Volcanic gases

228. Volatile material exhaled from volcanic vents, solfataras and fumaroles, some of which may be far from an active volcano, may be highly reactive and hazardous to humans and property. Although volcanic gases consist mainly of H_2O, they also include CO_2, SO_2, H_2S, CO, Cl, F, etc. which, in large amounts, can have serious health effects. Gases may be discharged in large quantities either from established vents or from new fissures unrelated to established vents, as in the case of Dieng (Java, Indonesia) in 1979, or from crater lakes as in the case of Lake Nyos (Cameroon) in 1987. Because these gases are usually heavier than air, they tend to follow drainage systems and collect in topographical depressions.

229. Hazards due to volcanic gases are assessed by mapping hydrothermal manifestations and considering topography, wind and weather patterns.

Ground deformation

230. Deformation driven by gravitational collapse of volcanic slopes, collapse of pit craters and grabens or shallow intrusion of magma are among the typical examples. Horizontal displacements of more than 100 m were produced by the 1977 eruption of Usu volcano in Hokkaido (Japan). Even the slow deformation of slopes may, with time, lead to considerable horizontal and vertical displacement manifested as faults, cracks and undulations of the surface. Significant ground deformation may occur as a result of magma injection during the formation of monogenetic volcanoes [32].

Earthquakes

231. Although it is not always easy to distinguish volcanic from tectonic earthquakes, only those directly associated with volcanic activity are considered here. These volcanic earthquakes usually occur in swarms and have a smaller magnitude than those of tectonic origin. They tend to vary widely in wavelength and frequency. Volcanic earthquakes can be large and numerous enough to cause moderate damage. Earthquakes of magnitude 6 or more have been cited as triggering eruptions, but this threshold is not always clear.

Tsunamis

232. Volcanogenic tsunamis may be generated when landslides, pyroclastic flows, debris avalanches, debris and lahars enter the sea or large lakes. These are also set off by the dislocation of the seafloor by offshore volcanic or seismic events. Collapse of a volcanic edifice triggered by volcanic eruptions or earthquakes may lead to large displacement of the slopes, which in turn can generate tsunamis. Many of the large historic disasters have been caused by tsunamis directly related to volcanic activity. Examples are the eruptions of Krakatau [9] and Mt. St. Augustine [33] and the collapse of a lava dome at Unzen volcano in 1792. The physical damage caused by tsunamis places them among the most serious volcanic hazards. Hazards due to tsunamis are evaluated based on the topography in the site vicinity, distance of the site from large bodies of water and bathymetry (see also IAEA Safety Guide No. 50-SG-10B).

Geothermal anomalies

233. Increases and fluctuations of ground surface temperature are frequently associated with volcanic activity. Formation of new fumaroles and steaming ground can destroy vegetation, destabilize slopes and cause subsidence. A groundwater system in which the thermal gradient is close to the boiling curve at depth can be destabilized by a large excavation that lowers the combined pressure and impedance of overlying rocks. In some cases, phreatic explosions occur, resulting in the formation of pit craters.

234. Evaluation of hazards due to the presence and development of hydrothermal systems around volcanoes is particularly important when considering calderas and volcanic complexes where hydrothermal systems can extend well beyond the edifice of the volcano. These hazards are often recognized by mapping alteration zones on and around the volcano, measuring soil degassing of ^{222}Rn, He, Hg, CO_2 and related gases, and through the use of geophysical surveys, particularly electrical surveys [34, 35]. Drilling provides information on the subsurface extent and temperatures of hydrothermal systems [36]. Models of multiphase flow and heat transfer in the hydrothermal system may assist in the assessment of how geothermal anomalies will respond to renewed volcanic activity or intrusion of magma [37–39].

Ground water anomalies

235. Volcanic activity, intrusions of dikes and sills, and associated crustal deformation may affect ground water level, and temperature, and alter the discharge of cold and hot springs and geysers. Such changes, if widespread, can affect the regional groundwater system. Techniques used to evaluate groundwater hazards resemble those used to evaluate geothermal anomalies. Groundwater hazards are evaluated using mapping, data from wells, and geophysical surveys. Numerical models of the impact of dike injection of regional groundwater flow have been developed [40].

Opening of new vents

236. Volcanic activity in a region can result in the formation of new vents. New vents may initiate along fissure zones that are up to several kilometres long, but normally eruptive activity localizes as the eruption continues, resulting in the formation of cinder cones and tuff rings. Interaction of magma with groundwater results in explosive activity and the formation maars and phreatic pit craters. Eruptions from new vents may last from several hours to years, as occurred during the formation of Volcano Parcutin, Mexico, between 1943–1952. Where associated with larger volcanic structures, such as shield volcanoes and calderas, new vents often form along rift zones or other major structures on the volcano. New vents also form in volcanic fields that are not associated with larger volcanic structures. Vent distribution within volcanic fields is sometimes partially controlled by regional structure and vents often cluster within volcanic fields. New vents can be the source of significant pyroclastic fall and voluminous lava flows.

237. The occurrence of a non-volcanic phenomenon like the so-called mud volcanoes may also be considered as an opening of a new vent. Mud volcanoes form by eruption of a suspension of rock particles with water and gas. They may be more than 100 m in radius and 20 m height. They occur both in volcanic areas (as at Etna) and in non-volcanic areas, that are usually characterized by clayey, silty and sandy bedrock formations. They form because of underground fluid overpressure, usually associated with high temperatures, that may cause fracturing and fluidization of the rock formation. The resulting suspension flowing upward erupts at the surface, forming flows. The gases, which may contain a relevant amount of methane, can burn to flames once in contact with the air. The eruption of mud volcanoes may be triggered also by the pressure waves associated with earthquakes and magmatic eruptions. The soil fluidization and mudflows could constitute potentially relevant causes of hazard. The mud volcano phenomenon is not addressed specifically in the present report and the criteria for determining capability and evaluating the related hazard should not be applied.

3. GENERAL REQUIREMENTS

301. During the initial stages of the siting investigations, all relevant data should be collected from available sources (publications, technical reports, and related material) in order to identify volcanic phenomena with potentially hazardous effects on the proposed nuclear power plant (see box 1, Fig. 1). The nature and amount of information required for an adequate evaluation of volcanic hazards depend mainly on whether or not active or potentially active volcanoes are present in the site region as defined in para. 403.

302. If evidence of historic volcanic activity in this region is found in the available records, a more detailed investigation should be performed to evaluate the volcanic hazard (see boxes 2 and 6, Fig. 1).

303. Even if no evidence of historic volcanic activity is found, a further investigation of the presence of volcanic rocks in the region is required. As a preliminary step, all available data of ages of volcanic rocks should be examined. If no volcanic rocks of Cenozoic age are found, no further volcanological studies are required (see boxes 3 and 9, Fig. 1).

304. If evidence of Cenozoic volcanism within the region is found, more detailed geological and volcanological information should be collected in order to define more precisely the age of this activity. This is particularly important where reliable age determinations are not already available.

305. Further investigations should be required if one or both of the following is found:
(1) evidence of Quaternary volcanism;
(2) evidence of Pliocene or Quaternary calderas or volcanic fields.
The objective shall be to determine the potential of renewed activity, herein referred to as capability (Section 5) (see box 5, Fig. 1).

306. All effects of capable volcanoes or volcanic fields, including historically active volcanoes, should be investigated in terms of their impact on the site (see box 6 of Fig. 1). The volcanic hazard evaluation should proceed in accordance with Section 6.

307. Potential effects of volcanism may result in site rejection. If the site is not rejected, the nuclear power plant should be protected from the potential effects of volcanism by either, (i) providing a safe distance and elevation to the site for the particular volcanic effect, or (ii) designing the plant to withstand the volcanic effect including all its consequences (see boxes 7 and 8, Fig. 1).

308. Under some circumstances it may be advantageous to monitor certain volcanoes throughout the lifetime of the plant in order to forecast their behaviour and potential effects on the site. In this case, a monitoring program should be prepared and implemented, preferably in co-ordination with competent specialized agencies in the country.

309. A quality assurance programme should be established and implemented to cover all activities related to data collection, data processing and interpretation, field and laboratory investigations, desk studies and evaluations that are within the scope of this report.

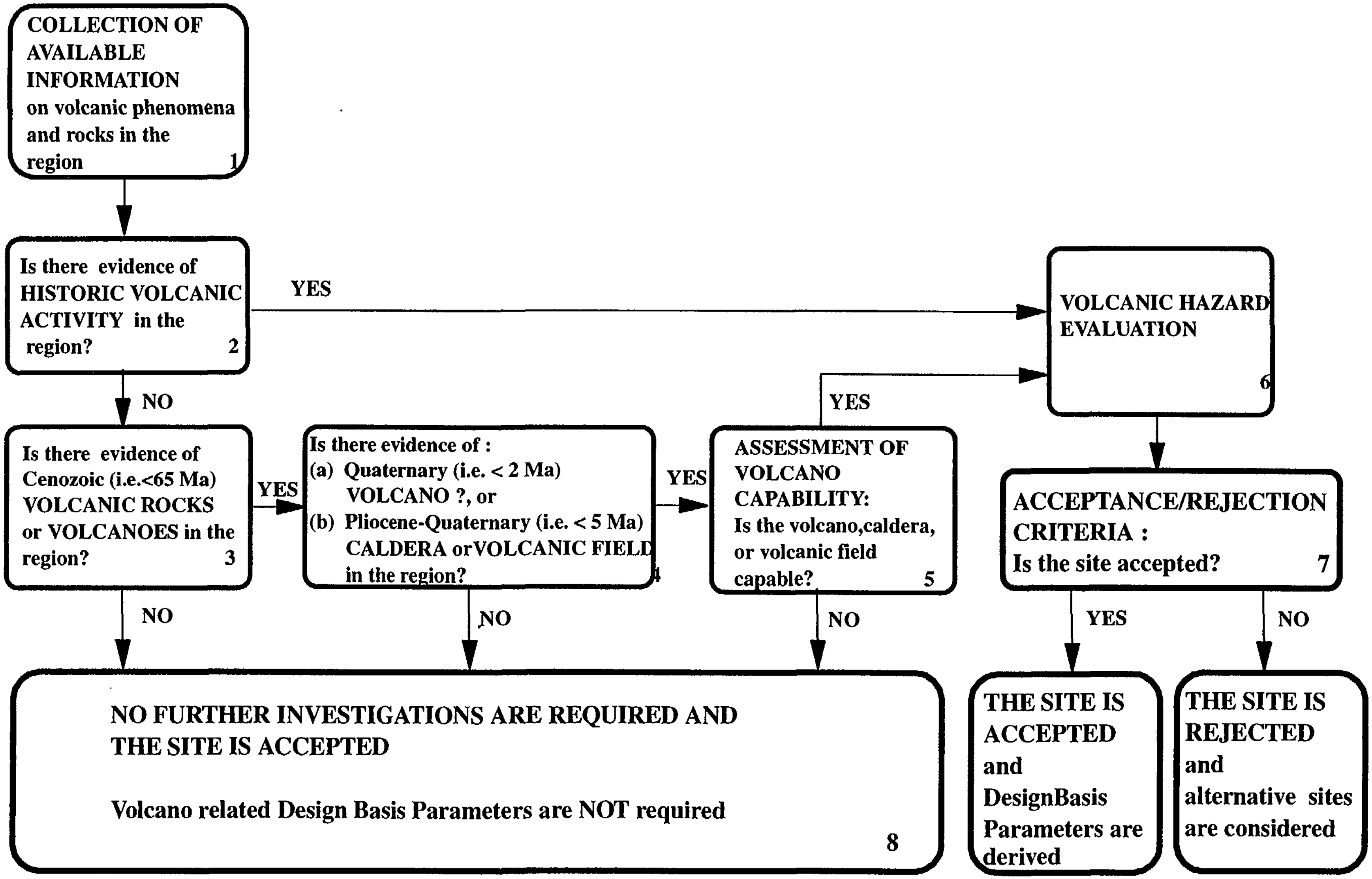

FIG. 1. Flow chart showing the process to satisfy the general requirements.

4. NECESSARY INFORMATION AND INVESTIGATIONS (DATABASE)

OVERVIEW

401. The validity of any assessment of volcanic hazards is dependent on a sound understanding of, (1) the regional geological and tectonic setting, and (2) the character of each individual eruptive center within the site region. To achieve this level of comprehension, it is necessary to compile integrated information for each of the volcanic provinces in the region. The characteristics of the volcanic province should first be related to the tectonic regime, taking into account both the past evolution of the region and its potential future development.

402. As discussed in Section 3, if Cenozoic volcanoes and volcanic fields and their products are identified within the region and their potential impact on the site is determined, these selected volcanoes or volcanic fields are then examined in greater detail in order to evaluate plausible types of eruptive behaviour that may significantly influence safety. The nature of the information required to do this depends on the scale of the study and the nature of the hazard being considered, as described below.

LEVELS OF STUDY

Regional studies

403. The goal of regional studies is to identify all volcanic phenomena that may impact the site. The regional scale investigation requires a compilation of all available and relevant geological, geophysical and volcanological information for Cenozoic volcanism in the region. All potential sources of volcanic phenomena listed in Section 2 located within this region should be identified. The typical radius of this area should not be less than 150 km from the site. This area may not be symmetrical, depending on the geology and physiography of the region. The information obtained in this study should be compiled on maps that are typically on a scale of 1:250 000.

404. The ages of Pliocene and Quaternary volcanic deposits having a regional extent of 100 km^2 or more should be defined by appropriate analyses such as stratigraphic methods and radiometric age determination.

405. Sources should be identified using regional geological data and reconnaissance mapping. As necessary, these data should be supplemented using isopach maps, distinctive petrographic and geochemical characteristics and topographic features that may influence the distribution of volcanic deposits.

406. Spatial and temporal trends in Pliocene and Quaternary volcanism should be identified.

407. The tectonic setting of Pliocene and Quaternary volcanism should be characterized.

408. In line with para. 305, volcanoes or volcanic fields identified in the regional survey may not require further study provided they meet either of the following criteria:

(a) the volcano has not been active in Quaternary time and has no manifestation of current magmatic activity;

(b) the caldera or volcanic field has not been active in the Pliocene and Quaternary and has no manifestation of current magmatic activity.

Studies of individual volcanoes and volcanic fields

409. Volcanoes and volcanic fields that have been identified in the regional survey as potential hazards to the site should be examined in more detail. In this regard, the following is required:

(1) Volcanoes or volcanic fields should be characterized in terms of morphology, eruptive products, and characteristic behaviour.

(2) The history of each volcanic centre should be determined in order to identify its evolutionary stage of development and its potential to generate each of the phenomena listed in Section 2.

(3) Records of other geologically analogous volcanoes should be used to provide a better perspective of the longterm development and possible future activity of the volcano. Information obtained from published and unpublished sources should be augmented by specific studies designed to acquire additional information of potential importance to the site. These studies normally include some combination of the following:

    (a) Geological mapping on a scale of 1:50 000 or less.
    (b) Geophysical surveys, including location of gravity and magnetic anomalies.
    (c) Geochemical analyses and petrologic models relating eruptive activity to compositional variations of the magma and the stratigraphic sequence.
    (d) Linking stratigraphic sequences and tephrachronology. This may entail both studies of surface exposures and drilling.
    (g) Radiometric age determinations of major eruptive units and key stratigraphic markers.

Site-specific studies

410. Together, these data will be used to establish the geologic history and structural evolution of the volcano or volcanic field. More detailed investigations should focus on (i) possible hazards originating in the site vicinity, and (ii) local conditions that could influence the impact of more distant events on the site. These studies should encompass the site vicinity (typically up to a radius of 10 km) with the specific objectives of assessing all potential volcanic hazards and delineating their possible influence on maps having a scale of 1:10 000 or less.

411. Potential hazards identified in this initial examination should be further analyzed to determine how the local conditions might influence the effects of close and distant events. These conditions include such factors as:

(1) meteorological, topographic and hydrologic conditions between the source and the site;
(2) geothermal or hydrothermal activity within the site area;
(3) man-induced disturbances of the thermal or hydrothermal regime.

VOLCANOLOGICAL DATABASE

412. Volcanological data collected for the region, individual volcanoes and the site should be stored in a database. This database should be developed and maintained by the organization responsible for further volcanic hazard assessment. The database is used to determine and document:

(1) the frequencies, repose intervals and durations of eruptions;
(2) spatial distribution of and structural controls on eruptions;
(3) styles of eruption and eruptive products;
(4) relationship between eruptive episodes and geochemical variation in magmatic compositions.

413. A catalogue should be compiled of all historically active volcanoes and areas of volcanic unrest identified as indicated in para. 403. Possible volcanological information to be obtained includes:

(1) date and duration of the eruption;
(2) nature of the eruptive products;
(3) areal extent and mass of eruptive products;
(4) seismic activity, ground deformation and other geophysical events;
(5) extent and pattern of damage;
(6) geochemical data.

414. The record of prehistoric activity should include descriptions of Pliocene and Quaternary volcanic products and phenomena listed in Section 2. The ages of major units should be related to the absolute geological time scale.

415. Information should be compiled on all potential sources of volcanic products that could reach the site. All Pliocene and Quaternary deposits in the site vicinity may be identified and evaluated according to the following information:

(1) identification of the source and distribution of the deposits;
(2) age and probable duration of associated eruption;
(3) composition and physical properties, including volume, density, probable temperature and time of deposition.

416. Additional information may be provided for each distinguishable tephra unit, including products of phreatomagmatic and phreatic eruptions, that may have impacted the site. This information includes isopach maps showing the extent, thicknesses, densities, particle sizes and dispersion axes of tephra units.

417. The following additional information should be provided for each distinguishable deposit produced by phreatomagmatic and phreatic eruptions, pyroclastic flows, surges or directed blasts that may have impacted the site:

(1) isopach maps showing thicknesses, densities, and probable velocities and temperatures;
(2) one or more maps identifying topographic features that influenced the direction and kinetic energy of flows driven by gravity or directed blasts. Areas over which such flows may have passed without leaving measurable deposits should also be shown.

418. The following additional information should be provided for each distinguishable deposit produced by lava flows, lahars, debris flows, and avalanches, any part of which is in the site vicinity:

(1) probable temperature, velocity, and kinetic energy at the site area;
(2) one or more topographic maps identifying topographic features that influenced the course, velocity and distribution of the flows.

419. The database should also contain the following additional information:

(1) seasonal wind directions and velocities as a function of elevation;
(2) maps identifying potentially unstable slopes that could result in avalanches;
(3) topographic maps and drainage patterns.

5. DETERMINATION OF CAPABILITY OF VOLCANOES

501. The concept of the capability of a volcano is introduced in order to define the state of a volcanic system and as a means for evaluating its potential reactivation. This section provides guidelines for assessing the capability of a volcano or a volcanic field.

502. The criteria for determining if a volcano or volcanic field is capable are the following:

(1) historical volcanic activity;
(2) manifestations of current magmatic activity;
(3) indication that the time elapsed since the last volcanic activity of a volcano or volcano field is not sufficiently long compared with the representative maximum repose interval for that specific volcano or volcanic field;
(4) indication that the last volcanic activity occurred more recently than the duration of the "increased extreme repose interval" for the volcano type, as defined in Section 506.

These criteria are applied in a hierarchical manner. If one or more of these criteria are met, then the volcano is considered to be capable.

503. A record of historical activity is clear evidence that a volcano is capable. Therefore, volcanoes that have been active in historical time are considered capable.

504. Manifestations of current magmatic activity indicate that a volcano or volcanic field is capable. Such manifestations include:

(1) geothermal activity;
(2) ground deformation;
(3) seismic activity;

in relation to volcanic activity as described in Section 2.

505. Repose intervals for volcanoes are normally established by age determination of volcanic eruptions. Repose intervals can be analyzed stochastically [4, 41–48]. A volcano can safely be considered not capable if it has been inactive for a time-period considerably longer than the representative maximum repose interval for that specific volcano.

506. In cases where adequate information is not available about the repose intervals for that specific volcano or volcanic field and, therefore, the representative maximum value cannot be used to determine capability, a volcano can safely be considered not capable if it has been inactive for a time period considerably in excess of the extreme repose interval for its type. This time period is called "increased extreme repose interval" and the excess with respect to the extreme repose interval for each volcano type takes into account a safety margin and the duration of the life of the volcano.[1]

[1]Annex II provides guidance to apply the criteria of para. 506. A tentative classification of volcano types is given, with indication of the increased extreme repose interval value applicable to each type.

6. EVALUATION OF VOLCANIC HAZARD

601. This section provides guidelines and procedures for evaluating volcanic hazards associated with capable volcanoes and volcanic fields when considering nuclear power plant site selection and design.

602. The manifestations of volcanic activity listed and described in Section 2 require primary consideration during the siting process. In each case it is necessary to determine whether:

(a) the site should be rejected because engineering solutions to mitigate the potential effects of such phenomena are either not practicable or cannot always be demonstrated as being adequate; or
(b) the site may be accepted and a design basis derived.

603. The volcanic phenomena which are listed in Table I should be used in consideration of site selection and design basis derivation. The last column refers to the NUSS Safety Guides that deal with similar external events and may be used as reference for derivation of an appropriate design basis. Phenomena identified as (1), (6), (7) and (12) may be considered either for site selection or design basis derivation depending on the magnitude of the event and the relative locations of the source and site.

604. The starting point of a volcanic hazard evaluation is the identification of all capable volcanoes and volcanic fields (i.e., sources of volcanic hazard, Fig. 2). For each volcanic source the following should be evaluated:

(i) phenomena that can be produced by the source;
(ii) activity history of the source.

605. Volcanic hazard evaluation for capable volcanoes and volcanic fields is based on deterministic and probabilistic methods.

606. For each phenomenon a conservative deterministic evaluation should be made for the purposes of screening. The following assumptions are normally part of this evaluation:

(1) An eruption occurs at each volcanic center, field or province at its closest approach to the site.
(2) The magnitude and duration are postulated to be the maximum potential eruption for this volcano (data from analogous volcanoes may also be used).
(3) It is further postulated that, in relation to the phenomena considered, unfavourable conditions of volcanic source exist which will have the greatest impact on the site. For example:

    (i) In the case of pyroclastic fall, the direction of wind is directly toward the site at a maximum credible velocity and at the elevation of the densest part of the eruption column for the entire duration of the eruption.
    (ii) In the case of avalanches, lahars, debris and pyroclastic flows, the source is assumed to be at the highest elevation and to have the greatest possible potential energy. Volumes are assumed to be the maximum observed on volcanoes of comparable form and activity.

TABLE I. PHENOMENA ASSOCIATED WITH VOLCANIC ACTIVITY

Type of phenomena	Primary consideration for:		
	Site acceptability	**Plant design**	**NUSS 50-SG-**
(1) Ballistic projectiles	x	x	S5/S11A
(2) Fallout of pyroclastic materials		x	S5
(3) Pyroclastic flows and surges	x		
(4) Air shocks and lightning		x	S5
(5) Lava flows	x		
(6) Debris avalanches, landslides and slope failures	x	x	
(7) Debris flows, lahars and floods	x	x	S8/S10A
(8) Volcanic gases		x	S5
(9) Ground deformation	x		
(10) Earthquakes		x	S1 (Rev.1)
(11) Tsunamis		x	S10B
(12) Geothermal anomalies	x	x	
(13) Groundwater anomalies		x	
(14) Opening of new vents	x		

607. The result of this evaluation will be a set of areas around the volcano within which the considered phenomenon should be further analysed. The distance from the source to the boundary of each such area is called the screening distance value (SDV) for the particular phenomenon. It follows that volcanic deposits within the site vicinity are direct evidence that the site lies within the SDV for that particular volcanic phenomenon.

608. For phenomena where the site is included within the SDV, further evaluation should be made to establish parameters for and quantify the effects of the phenomena at the site to decide whether or not an engineering solution is feasible to protect the plant from these effects.

609. Case I — If the volcanic source with which the phenomena is associated is a capable volcano active during the Holocene (as defined in Section 5), then the decision should be made on the preceding deterministic evaluation concerning:

(a) acceptability of the site,
(b) derivation of engineering design bases

for the plant in relation to each phenomenon originating from this source. Holocene volcanoes that have not erupted historically are included in Case I because the Holocene is a sufficiently long period of time compared to the lifetime of the nuclear power plant whereas the length of the historical record varies by country or region. This deterministic evaluation may be made for each volcanic phenomenon individually. Only volcanic phenomena produced by Holocene eruptions need to be considered deterministically. All other volcanic phenomena described in Section 2 should then be evaluated probabilistically. For example, if a volcano has produced only ash falls during the Holocene, only these phenomena need be considered deterministically. Volcanic hazards related to other phenomena, pyroclastic flows for example, may be evaluated using probabilistic methods.

610. Case II — If the volcanic source with which the phenomenon is associated is not a historical or a Holocene volcano but is postulated to be capable as a result of the evaluation of investigations recommended in Section 5, the following method is recommended:

(i) Using the record of activity of the source or of analogous volcanoes, a statistical/stochastical evaluation should be made to determine spatial and temporal patterns and trends.
(ii) For each type of phenomenon, a statistical/stochastic analysis should be performed to determine recurrence rates and/or the probabilities of events having a range of possible severities, and using observations of analogous volcanoes.
(iii) Decision on the acceptability of the site with respect to each phenomenon should be made on the basis of probabilities associated with each phenomenon. The level of acceptable probability for each phenomenon is a function of its effect on the site. These probability levels should have the same order of magnitude as similar events considered in the external hazard evaluation for the site (such as earthquakes, an airplane crash, etc.).
(iv) If the site is found to be acceptable for all phenomena, the engineering design bases should be derived deterministically as described in para. 606.

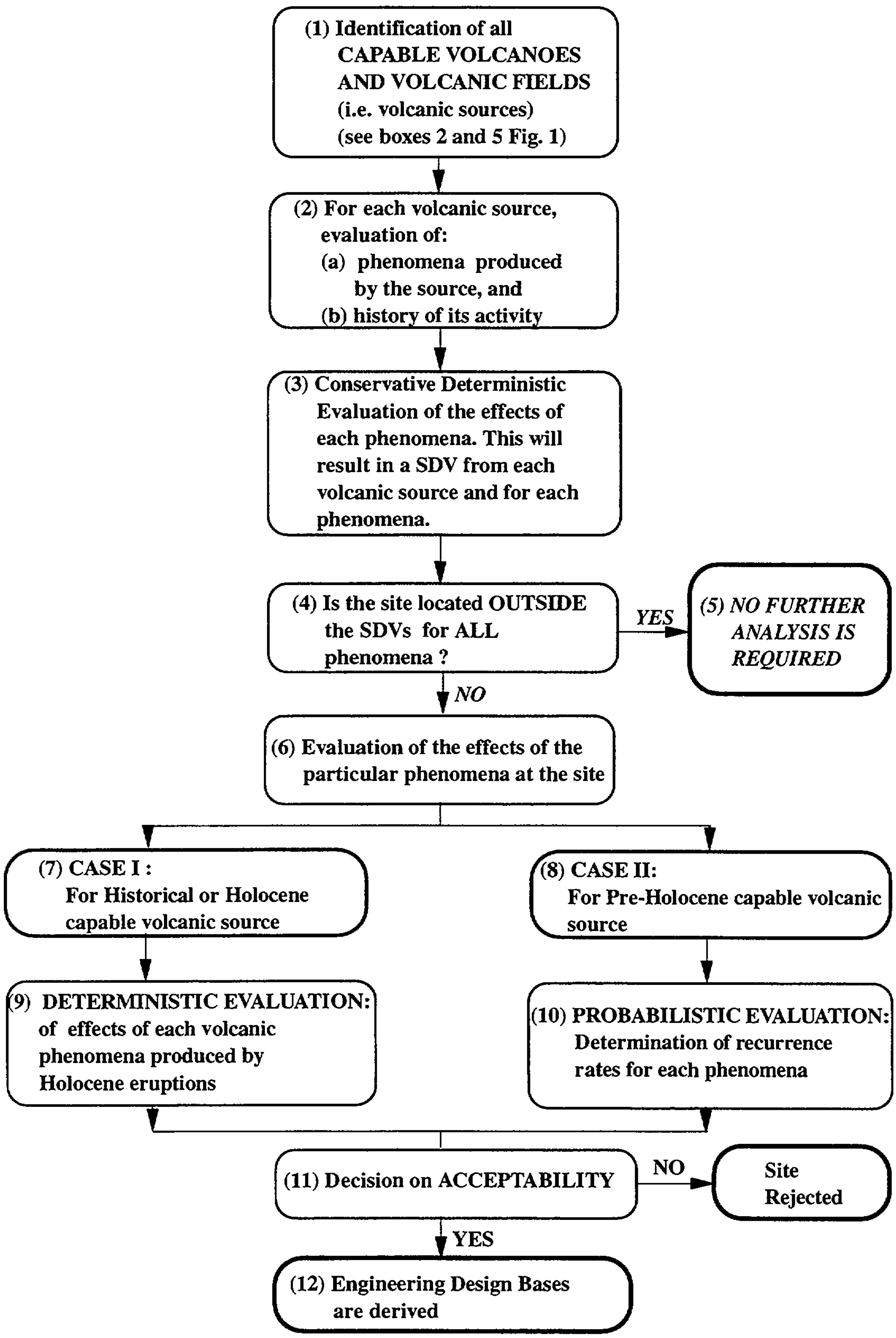

FIG. 2. Flow chart for volcanic hazard evaluation.

7. DESIGN CONSIDERATIONS

701. A combination of deterministic and probabilistic approaches is used to decide whether or not an acceptability problem exists for the site due to volcanic hazard (Section 6). If it is demonstrated that the plant can be protected from volcanic hazards through design measures only (i.e. the site does not need to be changed), then a set of design basis parameters should be derived to account for all the effects to which the plant may be subjected (para. 606). Alternatively, it may be demonstrated through a more refined analysis that the effect does not need to be considered.

702. Each effect which is included in the design basis should be associated with a parameter and quantified so that it can be compared with the design basis values of other external events to the extent possible. For some of the effects it may be possible to demonstrate that design basis parameters derived for other external events envelope those derived for volcanic hazards.

703. In relation to design, the following observations can be made regarding each phenomenon listed in Table I.

BALLISTIC PROJECTILES

704. Ballistic projectiles can be compared with impacts due to tornado-borne missiles or aircraft crashes. However, a very significant difference would be the number of missiles which can be expected to fall on a site. A size/distance distribution of the projectiles would show that, in fact, larger pieces may travel farther due to the decrease of the influence of drag forces (para. 202). In general, it would be expected that nuclear power plants are sited sufficiently far ($\geq$10 km) from the source of ballistic projectiles.

FALLOUT OF PYROCLASTIC MATERIALS

705. Ash fall is the most widespread phenomenon due to volcanoes. The main parameters for consideration are the expected thickness, particle size and density, and rate of accumulation of ash at the site. Consequences of substantial ash fall would be the static vertical load on structures, potential blockage of cooling water intake systems and adverse effects on all ventilation systems. The static vertical load should be compared with other loads of this kind (e.g., snow load) in order to decide whether an envelope is already provided. Adverse effects of ash fall on water intake and ventilation systems should be considered and alleviated through a combination of engineering design and administrative measures.

PYROCLASTIC FLOWS AND PYROCLASTIC SURGES, AND LAVA FLOWS

706. It is generally not feasible to protect a nuclear power plant from lava flows, pyroclastic flows or pyroclastic surges by engineering solutions.

AIR SHOCKS AND VOLCANIC LIGHTNING

707. Air shocks are also limited in their radius of influence. In any case, protection against such pressure waves is common for most nuclear power plants because of considerations for external man-induced events, e.g. pipeline accidents, accidents involving transport of explosive material or external natural events, e.g. extreme meteorological phenomena, such as tornadoes.

708. Volcanic lightning is similar to lightning caused by extreme meteorological events (see IAEA 50-SG-11A). Protection of the plant against volcanic lightning can be achieved by engineering design measures.

DEBRIS AVALANCHES, LANDSLIDES AND SLOPE FAILURES

709. Debris avalanches should be considered separately from other slope failures mainly because of the very large volume involved and the high velocities of the avalanche. It may not be feasible to provide engineering design to protect the nuclear power plant against this phenomenon. Other, smaller scale slope failures can be treated within the scope of other (i.e. non-volcanic) geotechnical hazards. Decisions on how to protect the plant against these hazards should be made on a case-by-case basis.

DEBRIS FLOWS, LAHARS AND FLOODS

710. These phenomena can be considered together with floods of non-volcanic origin. Protection of the plant against these phenomena would normally entail having a 'dry site'. An important difference of these phenomena from ordinary floods is the short time of warning available after the onset of the flow. High flow velocities and high flow volumes should also be expected. In some areas it may not be possible to protect the nuclear power plant from lahars by engineering solutions.

VOLCANIC GASES

711. The flow paths, types and expected concentrations of gases should be estimated at the site. The methods would be similar to the treatment of hazards from gases originating from man-made sources. The adverse effects of volcanic gases include toxicity and corrosion. Protection of plant personnel should be ascertained through engineering solutions and administrative measures.

GROUND DEFORMATION

712. Generally, it is considered that engineering solutions are not feasible to provide protection against large ground deformation.

EARTHQUAKES

713. The effects of a volcanic earthquake to a nuclear power plant are similar to those of a tectonic earthquake. Therefore, identical methods can be used in their analysis (see IAEA Safety Series Nos 50-SG-S1 (Rev. 1) and 50-SG-D15).

TSUNAMIS

714. Volcanoes are only one source of tsunamis. These should be considered within the framework of coastal flooding assessment. As in the case of river flooding, the protection of the plant would entail the provision of a 'dry site'.

GEOTHERMAL AND GROUNDWATER ANOMALIES

715. Geothermal and groundwater anomalies should be considered both for their direct effects at the site (i.e. change in the design basis water level) as well as the impact of secondary

hazards such as landslides and subsidence. Although minor fluctuations in geothermal and groundwater conditions would be tolerable and protection can be provided through engineering design, extreme cases could be impossible to cope with.

OPENING OF NEW VENTS

716. Generally, it is considered that engineering solutions are not feasible to provide protection of the nuclear power plant against the formation of new vents.

8. MONITORING SYSTEMS FOR VOLCANIC ACTIVITY

OBJECTIVE AND METHODS OF MONITORING

801. In some cases, monitoring of capable volcanoes may be useful. If a decision is made to monitor the activity of a volcano, the type and extent of monitoring should be selected according to need and on a case-by-case basis. Different ways of monitoring volcanoes are briefly described in this section.

802. If a volcano is monitored in relation to some effect it may have on the site, due consideration should be given to this within the framework of the emergency plan of the nuclear power plant as recommended by the Code (para. 334). A detailed procedure should be prepared to consider and/or respond to anomalies detected by the monitoring system.

803. If available, close co-operation with existing surveillance systems such as those utilized by national programmes for prediction of volcanic eruptions and mitigation of disasters is recommended. Exchange of observational data and consultation with experts in volcanology working in such programmes generally provide invaluable benefit.

VOLCANIC EARTHQUAKES

804. Instrumental monitoring of earthquakes by a network of high sensitivity seismographs is one of the best methods of surveillance of volcanic activity. It is widely accepted that explosive activity of volcanoes can be closely characterized by microearthquakes occurring within or close to a volcanic edifice. It is often possible to forecast the onset of an eruption by closely monitoring seismic activity.

805. Currently, the best method of monitoring seismic activity of a volcano is to continuously operate a telemetered network of seismographs connected to an on-line computer processor which can locate epicentres and estimate the magnitude and other characteristic parameters on a real time basis.

806. Even where no eruptive activity is detectable, temporary network observations may be useful for gathering information on the background level of seismic activity of the area.

GROUND DEFORMATION

807. Ground deformation can be detected by repeated geodetic measurements. Changes of horizontal distance may be monitored by repeated measurements with laser geodimeter and Global Positioning Systems (GPS). Vertical changes are monitored by repeated precise levelling, GPS systems, tide gauges (on the sea coast), etc. Very small changes in gradients of the earth's surface are detectable by high sensitivity tiltmeters. Strain gauges placed in boreholes can pick up changes of crustal stress fields. All these methods are useful in monitoring ground deformation and changes in volcanic topography that may reflect underground movement of magma and other fluctuations in volcanic activity.

CHANGES IN GEOMAGNETISM AND GEOELECTRICITY

808. Measurements of geomagnetic and geoelectrical parameters may be useful to understand the underground structure, position of magmatic body and water systems and to detect any changes thereof. Observation of spatial distribution and temporal variation of the total force

of the geomagnetic field, self potential and resistivity, using various methods and instruments, may lead to a better understanding of the movement of the magmatic body and other possible heat sources.

809. Resistivity assessment by magnetotelluric methods using various frequencies can reveal underground resistivity profiles which can be interpreted as indicators of water-rich layers, various strata and magma body.

GRAVITY

810. Measurements of gravity over the volcanic terrain give useful information on underground structure as well as rock properties such as porosity and mass density. When detailed measurements on the temporal variations of gravity can be made, the possibility of finding movement of magmatic body and the change of underground structure may be significant.

GASES

811. Volcanic gases discharged out of the crater, fumarole, solfatara, etc., as well as soil gases, give useful clues as to the degree and character of volcanic activity. Chemical substances of interest include SO_2, H_2S, CO_2, CO, H_2, CH_4, F, Cl, NH_3, He, Rn, Ar and other gases.

812. Remote measurement of SO_2 in a gas plume using a correlation spectrometer is useful for monitoring volcanic activity.

813. Analyses of leachate from ash and sublimates may be good indicators of magmatic activity (e.g., Cl/S ratio).

814. Variations of isotopic composition of He sometimes accompany changes in volcanic activity.

815. Continuous visual observation of the amount, colour and other features of the volcanic plume rising from a crater may be important and is easily practiced.

GEOTHERMAL ANOMALY

816. Changes of temperature of volcanic gases issuing from fumaroles, craters and solfataras, of hot and cold spring waters are all good indicators of variations in volcanic activity. Continuous recording or field measurement at fixed intervals of such temperatures are recommended. Migration of geothermal fields and steaming grounds, anomalous melting pattern of snow fields, etc., are good indicators of the changes of the underground geothermal regime.

COLD AND HOT SPRINGS

817. Fluctuations in water level, changes in chemical composition, temperature, acoustic analysis and flux of crater lakes and spring water often reflect variations in volcanic activity.

OTHER OBSERVATIONS

818. By repeated visual inspections from a distance or on the volcano close to the crater, it is often possible to detect the first symptoms of change in volcanic activity. Such features include anomalous sounds like rumblings, fluctuations of fumaroles and solfataras, patterns of snow melting, drying up of wells, springs, lakes and vegetation.

Annex I

MAJOR DIVISIONS OF GEOLOGICAL TIMES

Era	Period	Epoch	Millions of years ago
Cenozoic	Quaternary	Holocene	0.01
		Pleistocene	2
	Tertiary	Pliocene	5
		Miocene	24
		Oligocene	38
		Eocene	55
		Paleocene	65
Mesozoic	Cretaceous		144
	Jurassic		213
	Triassic		248
Palaeozoic	Permian		286
	Carboniferous		360
	Devonian		408
	Silurian		438
	Ordovician		505
	Cambrian		590
	Precambrian		> 590

Annex II

CLASSIFICATION OF VOLCANOES FOR CAPABILITY ASSESSMENT

The concept of the capability of a volcano is introduced in the present report in order to define the state of a volcanic system and as a means for evaluating its potential reactivation. As indicated in Section 3, guidelines for assessing the capability of a volcano or volcanic field are provided in paras 502–506.

In this regard, and considering that the main factors related to the episodic behaviour of volcanic activity are the duration of the active period and the repose interval between two consecutive active periods, an example of a specific classification of volcanoes according to their eruptive behaviour is provided in this Annex as a tool in support of the capability assessment. The principal types of volcanoes recognized in the studies described in Section 4, and required for capability assessment as indicated in paras 502 (4) and 506, are classified according to the following categories:

1. CALDERA SYSTEM

Calderas characterized by ash-flow volcanism are considered. They are mostly related to subduction-related arcs, or, more rarely, to continental rift systems or hot spots. The dominant composition of the erupted products is usually rhyolitic to dacitic but there are also a number of andesitic, trachytic and even basaltic calderas. Calderas are typically characterized by large (>2 km) subcircular depressions which result from the evacuation of the top of a magma chamber during an explosive eruption which can last from hours to several days. In some cases there is only one paroxysmal pyroclastic eruption which is subsequently followed by intracalderic activity such as the emplacement of silicic domes. In other cases periodic injections of mafic magma at the base of a silicic magma chamber may trigger new pyroclastic eruptions. Caldera complexes constituted by clusters of several calderas are found at the top of large magma chambers of batholithic dimension.

Large caldera complexes can remain active for millions of years and may have repose intervals of hundreds of thousands of years. Renewed eruptive episodes at calderas may involve the formation of other volcano types and/or new caldera formation. Younger calderas are usually spatially distinct from older calderas. In the absence of other information, the increased extreme repose period for calderas is on the order of hundreds of thousands of years.

2. STRATOVOLCANOES

This category includes composite volcanoes resulting from both effusive and explosive eruptions. They may occur in different geodynamic settings. Their products range in composition from rhyolites to basalts, but are more often andesitic. Intermediate to silicic volcanoes usually have only a central vent. Mafic stratovolcanoes may have lateral eruptions from fissures and parasitic vents. Stratovolcanoes usually pass through different stages of activity with different explosivity and repose intervals. Sector collapses with formation of debris avalanches are common processes both for continental and oceanic stratovolcanoes [23, 24, 49] and can occur several times during the life of a volcano.

Individual stratovolcanoes are known to continue to be active for hundreds of thousands of years and can have repose intervals as long as thousands of years between eruptive episodes. Renewed activity nearly always occurs at a central vent or crater. Occasionally flank eruptions or crater migration may occur. Individual eruptive episodes at stratovolcanoes commonly last months and sometimes much longer. In the absence of other information, the increased extreme repose period for individual stratovolcanoes is in the order of 10 000 years.

Young stratovolcanoes frequently overlie or are adjacent to older extinct stratovolcanoes, forming complexes [50]. Stratovolcano complexes may be active for a million years or so. Therefore it is critical to document the volcanological evolution of the complex. In the absence of additional information the increased extreme repose period for stratovolcano complexes is in the order of one million years.

3. SHIELD VOLCANOES

Shield volcanoes result mainly from eruptions of basaltic lava flows. Shields range in size from small lava mounds, only a few cubic kilometres in volume, to very large mountains (Hawaii). They form gentle sloping (<5°) cones, often with effusion from rift zones characterized by alignments of scoria and spatter cones, eruptive fissures and pit craters.

Shield volcanoes are characterized by eruptive episodes that can last several years to decades, during which eruptions can be very frequent or more or less continuous. Renewed eruptive activity commonly occurs in a central vent, a flank rift zone, or elsewhere on the flanks of the volcano. The location of active vents often changes during individual eruptive episodes. The longevity of shield volcanoes varies from years to millions of years. Because of this tremendous variation in longevity, it is impossible to estimate an increased extreme repose period for shield volcanoes in general. For shields that can be demonstrated to be monogenetic (built during one eruptive episode), the increased extreme repose period may be as short as 1000 years. For large, polygenetic shield volcanoes, the increased extreme repose period may be as long as 100 000 years, although this needs some further discussion because the repose period for some large shield volcanoes is likely much shorter than that.

4. FIELDS OF MONOGENETIC VOLCANOES AND FISSURES

Fields of monogenetic volcanoes contain small (less than 1 km^3) cinder cones, maars, tuff cones, tuff rings and lava domes, produced during a single eruption which can last from several days to a few years or, in rare cases, decades. Cinder cones are formed by scoria, ash, bombs and brecciated lava flows. They are the products of repeated but short-lived strombolian activity of basaltic and basaltic-andesitic composition. Maars, tuff rings and tuff cones are monogenetic landform produced by phreatomagmatic eruptions. They are formed by volcanic craters with low rims made by wet surge deposits and minor ash falls and breccias. Maars have the floor level below the surrounding areas and are frequently occupied by lakes. Lava domes are bulb-shaped bodies updoming pre-existing rocks or extrusion of short, stubby lava flows, often associated with autoclastic material and hot avalanche deposits. These monogenetic centres are commonly clustered in volcanic fields with hundreds of elements or may constitute linear chains which follow tectonic structures. Cinder cones may also be found along rift zones on the flank of large shield volcanoes.

Groups of monogenetic volcanoes are commonly active for a few million years and can have repose periods between the formation of new volcanoes ranging from thousands to a few hundred thousands of years. Renewed eruptive activity normally involves the formation of a new monogenetic volcano. In the absence of additional information the increased extreme repose period for volcanic fields is in the order of 5 million years [51–53].

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GLOSSARY OF VOLCANOLOGICAL TERMS

Active volcano

A volcano that is erupting, has erupted historically or has other evidence of volcanic unrest.

Andesite

A dark, fine-grained, commonly porphyritic volcanic rock with 53 to 63% SiO_2.

Ash

Fine pyroclastic ejecta with particles less than 2 mm in diameter.

Basalt

A dark, fine-grained, commonly vesicular volcanic rock with 45 to 53% SiO_2.

Base surge

A ring-shaped cloud of gas and suspended solid debris that moves outward at high velocity from the base of an explosion column, commonly associated with phreato-magmatic eruptions.

Block

An ejected fragment of solid rock with angular form and a diameter greater than 64 mm.

Bomb

A fragment or rounded mass of magma ejected while still fluid enough to become rounded or distorted in flight. It is larger than lapilli (64 mm) and unlike a block, does not have an angular form unless broken on impact.

Caldera

A large basin-shaped volcanic depression, more or less circular in form, the diameter of which is many times greater than that of the included vent or vents.

Capable volcano

A volcano that has a significant probability of future activity during the lifetime of the nuclear power plant.

Collapse pit

A volcanic depression, normally with steep walls and a diameter less than a kilometre, formed primarily by subsidence.

Composite volcano

(See **stratovolcano**.)

Crater

A basin- or funnel-shaped depression, usually formed by explosive eruptions at or near the summit of a volcano. The diameter of the floor is the same or slightly larger than that of the vent. (See also **collapse pit** and **caldera**.)

Dacite

A fine-grained, commonly porphyritic volcanic rock intermediate between andesite and rhyolite.

Debris avalanche

A sudden, gravity driven flow of rock and other debris, often with substantial amounts of water, but little, if any, new magmatic component.

Directed blast

Debris propelled explosively, usually at a low angle, from a dome or the over-steepened flank of a volcano.

Dome

A steep sided, bulbous extrusion or shallow intrusion of viscous lava.

Ejecta

Material thrown out explosively from a volcanic vent (synonym: pyroclasts).

Eruption, types of

(See **phreatomagmatic**, **plinian**, **strombolian**, **vulcanian**.)

Eruption column

A stream of volcanic gas and fragmental debris ejected more or less vertically from a volcanic crater, fissure, or dome.

Eruptive episode

A series of volcanic events within a statistically distinguishable period of time preceded and followed by a period of repose.

Eruptive event

A period of essentially continuous or pulsating discharge of gas, liquid or solids from a volcanic vent.

Extinct volcano

A volcano that is not presently erupting and is not expected to do so in the future.

Felsic

A descriptive term applied to silica-rich rocks composed in large part of light-colored minerals, such as feldspar and quartz.

Fumarole

A vent, usually volcanic, from which gases and water vapour are emitted.

Gas jet

The lower part of a high velocity eruption column.

Geothermal

A descriptive term used for conditions or processes related to the earth's internal heat.

Hazard

(See **volcanic hazard**.)

Holocene

A period of the Quaternary era from the end of the Pleistocene to the present (the last 10 000 years; synonym: recent, post-glacial, see Annex I).

Hydrothermal manifestation

Volatile rich emissions, normally at temperatures below 1000°C, and rich in water, carbon dioxide, and sulphur gases. The term is also used for the deposits and altered rocks that are associated with such emissions.

Ignimbrite

A rock formed by deposition of pyroclastic material, commonly pumiceous and of large volume, that has flowed across the surface of the ground. It may be indurated by compaction.

Isopach

A line drawn on a map through points of equal thickness of one or more stratigraphic units.

Isopleth

A line along which all points have numerically specified constant or equal values for a particular variable, element, or quantity with respect to space or time.

Lahar

A flow of poorly sorted heterogeneous volcanic debris of all sizes mixed with water at temperatures less than boiling. May be formed during an eruption or by later process or slope instability.

Lapilli

Pyroclastic ejecta in the size range of 2 to 64 mm.

Lava

A general term used for both a largely molten extrusion and the solid rock that results from its cooling.

Maar

A low-rimmed volcanic crater formed by a single explosive episode. Its floor is lower than the original ground surface, and it may contain a shallow lake (see **tuff ring**).

Mafic

A descriptive term applied to rich-poor rocks composed in large part of dark colored minerals, such as pyrocene, amphibole, olivine and iron-titanium oxides.

Magma

Molten or partially molten rock within the earth that is capable of flow. Magma is derived from the partial melting of the crust or mantle, often in the presence of volatiles.

Magma chamber

Space in the crust where magma is stored and can rise and be discharged in volcanic eruptions.

Mofetts

Gas vents with temperatures below the boiling point of water and with CO_2-dominated gases.

Monogenetic cone

A volcanic edifice built during a single eruption, usually of small dimensions and characterized by a single eruptive style that may produce both scoria and lava.

Mud volcano

A round-like accumulation, usually small and conical, formed by clay, clastic particles, water and gas discharged in non-volcanic as well as volcanic areas.

Obsidian

A dark, lustrous volcanic rock composed mainly of volcanic glass.

Petrography

The branch of geological science that deals with descriptions and systematic classification of rocks according to their mineral components and microscopic textures.

Phreatic

Pertaining to meteoric water. (See **phreatomagmatic**.)

Phreatomagmatic

Explosive activity that produces both magmatic gases and steam, along with solid debris consisting of both fresh volcanic glass and fragments of older rocks; caused by contact between magma and water.

Plinian eruption

A type of eruption characterized by large gas-rich explosions propelled as powerful columns or gas and pyroclastic debris that may rise to heights of several kilometres. Often associated with pyroclastic flows and formation of calderas following discharge of large volumes of magma.

Pyroclastic

An adjective denoting fragmental products produced by explosive eruptions, normally at high temperature (see **volcaniclastic**.)

Pyroclastic fall

Tephra that has been ejected at a high angle and deposited by falling through the atmosphere.

Pyroclastic flow

Solid fragments, with or without molten particles, suspended in hot, expanding gas and propelled by gravity as relatively dense turbulent suspension moving over the ground surface.

Pyroclastic surge

An expended turbulent gas-solid suspension propelled at high velocity by a sudden release of gas. In contrast to pyroclastic flows, gravity is a minor component of the driving force and topographic barriers are more easily surmounted.

Pumice

Highly vesicular felsic glass of intermediate to siliceous composition related to explosive eruptions of gas-rich viscous magma. It may have a wide range of grain size.

Quaternary

A period of geologic time including the Pleistocene and Holocene epochs beginning approximately two million years ago and continuing to the present (see Annex I).

Radiometric age

A time interval, normally measured back from the present, on the basis of the rate of decay of radioactive species. Carbon-14, potassium–argon, and argon–argon dating are the quantitative methods most commonly used for volcanic rocks.

Rhyolite

A fine-grained, commonly porphyritic or glossy volcanic rock with more than 68% SiO_2.

Scoria

Dark colored, highly vesicular pyroclastic fragments of basaltic or andesitic composition.

Scoria (or cinder) cone

Small conical landform typically formed by Strombolian eruptions and constituted mainly of scoria and bombs.

Shield volcano

A volcano with gentle slopes formed primarily by fluid lavas.

Solfataras

Vents from which volcanic gases rich in sulphur (SO_2, H_2S, etc.) are released at the ground surface.

Stratovolcano

A large steep-sided volcano composed principally of fragmental ejecta interbedded with lava and lahars.

Strombolian

A type of eruption characterized by explosive ejection of incandescent bombs and scoria, often in close association with scoriaceous lavas, usually of small volume.

Tectonics

A branch of geology dealing with the broad architecture of the upper part of the Earth's crust in terms of the origin and historical evolution of regional structural or deformational features.

Tephra

A general term for all types of pyroclastic materials.

Tsunami

A large wave triggered by earthquakes, explosive volcanic eruptions, or large landslides and avalanches usually in the sea.

Tuff ring

A low-rimmed, volcanic crater formed by a single eruption or series of closely spaced explosive eruptions. The floor is above the original ground surface (see **maar**).

Volcanic centre

(See **volcano**.)

Volcanic earthquake

Earthquake caused by volcanic explosions, subsurface movement of magma, or collapse or displacement of parts of the solid edifice.

Volcanic field

A group of related monogenetic volcanoes formed over a period of time, in a region with a radius of ten to a few hundred kilometres.

Volcanic gas

Gas released from magma, normally with large proportions of H_2O, CO_2, and sulphur gases.

Volcanic glass

Vitreous material derived from rapidly cooled viscous magma.

Volcanic hazard

A volcano-related condition that is potentially detrimental to life and property.

Volcanic province

The region in which the volcanism is related to a common geodynamic regime and geological history.

Volcanic vent

The orifice from which volcanic products are emitted.

Volcaniclastic

A general term used for any fragmental material derived mainly from volcanic rocks. The fragmentation may be due to volcanic eruptions, as in the case of pyroclastic ejecta, or to non-volcanic processes, as in the case of epiclastic material resulting from mechanical weathering and erosion (see **pyroclastic**).

Volcano

A name applied to both the vent from which magma or gas are discharged and to the morphological feature formed by accumulation of the products of its eruptions.

Volcanology

The study of the origin, transport, and eruption of magma.

Vulcanian

A type of volcanic eruption characterized by large amounts of gas and lithic particles but little or no lava. The ejecta are not normally incandescent.

CONTRIBUTORS TO DRAFTING AND REVIEW

During the development phase, the following experts participated in one or more of the meetings (1993–1994):

Aramaki, S.	Nihon University, Japan
Godoy, A.	International Atomic Energy Agency
Gürpinar, A.	International Atomic Energy Agency
McBirney, A.	University of Oregon, United States of America
Ogata, S.	NEWJEC Inc., Japan
Pasquaré, G.	University of Milano, Italy

During the revision phase, the following experts participated in one or more of the meetings (1995):

WORKING GROUP AND TECHNICAL COMMITTEE:

Aramaki, S.	Nihon University, Japan
Connor, C.B.	SW Research Institute, United States of America
Elgohary, M.	AECL, Canada
Eyidoğan, H.	Istanbul Technical University, Turkey
Karyono, Ir.	National Atomic Energy Agency, Indonesia
Löw, S.	Colenco, Switzerland
McBirney, A.	University of Oregon, United States of America
Pasquaré, G.	University of Milano, Italy
Serva, L.	ANPA-DISP, Italy
Voborny, O.	Colenco, Switzerland

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