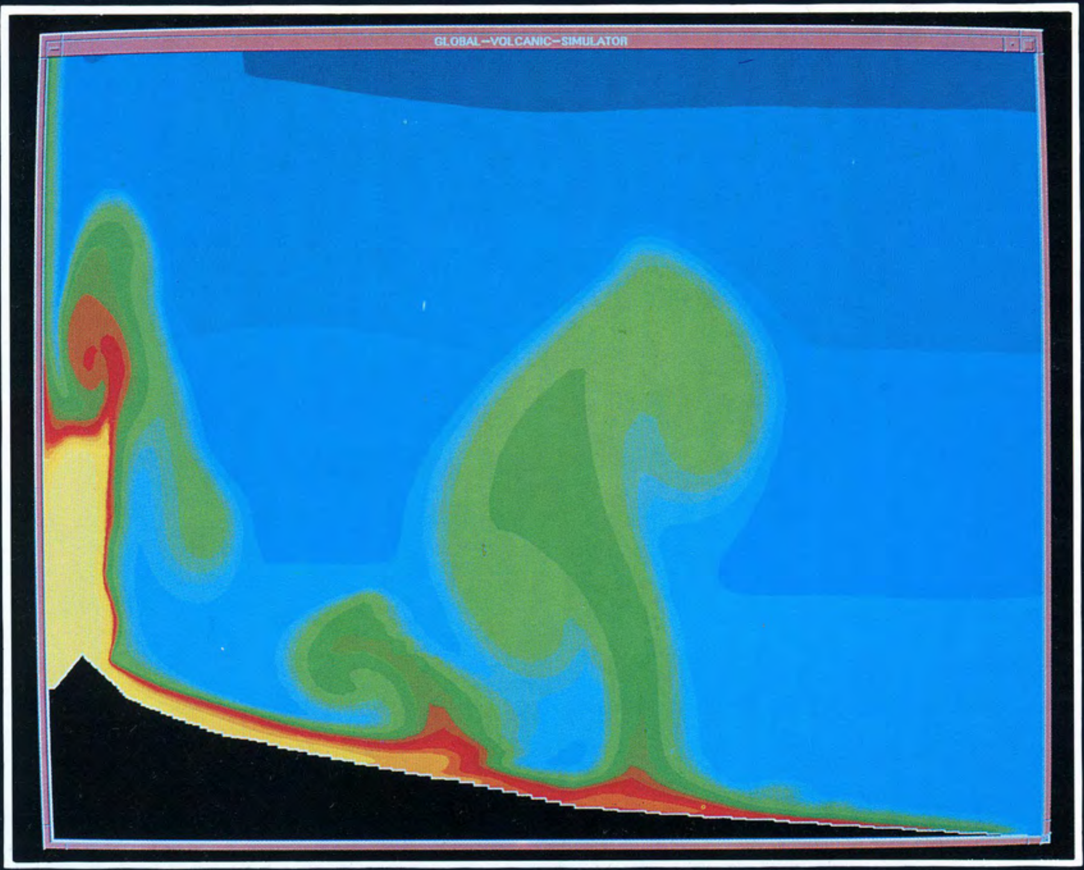
C.N.R. - GRUPPO NAZIONALE PER LA VULCANOLOGIA
ITALY

Flavio Dobran

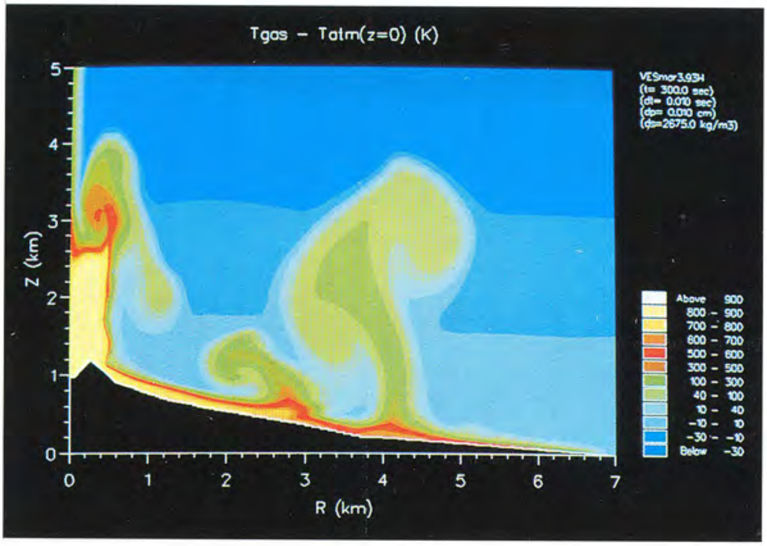
Global Volcanic Simulation of Vesuvius

With a contribution by Raffaello Trigila

Prologue by Franco Barberi



GIARDINI



The figure displays the temperature distribution in the atmosphere and pyroclastic flow moving along the slope of Vesuvius at 300 s following a plinian-type eruption which produced the collapse of volcanic column. The eruption occurs from a circular vent at 965 m altitude inside a crater and is symmetric about the axis of the vent at R=O. The vent conditions were established by modeling the ascent of gray magma of the AD 79 eruption of Vesuvius (Dobran and Papale, 1992c). These conditions involved: mass eruption rate = 1.5×10^8 Kg/s, initial dissolved water content = 2 wt%, temperature = 1123 K, and conduit length = 5 Km. The simulation was carried out by a complex two-phase flow model of Dobran et al. (1992) with the vent conditions: diameter = 100 m; temperature = 1123 K; pressure = 0.55 MPa; velocities of gas and pyroclasts of 274 and 144 m/s, respectively; pyroclasts size = 100 μm, and pyroclasts volumetric fraction = 0.05. The column built a fountain at about 2 Km above the vent, partially collapsed and formed a radially spreading pyroclastic flow which at about 200 s formed a phoenix column at a distance of about 4 Km from the vent. At 300 s displaced in the figure, the phoenix cloud has developed into a large volcanic plume and the head of the pyroclastic flow has reached the Tyrrhenian sea 7 km away from the vent.

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Global Volcanic Simulation of Vesuvius

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GIARDINI

Ben mille ed ottocento
anni varcàr poi che spariro, oppressi
dall'ignea forza, i popolati seggi,
e il villanello intento
ai vigneti, che a stento in questi campi
nutre la morta zolla e incenerita,
ancor leva lo squardo
sospettoso alla vetta
fatal, che nulla mai fatta più mite
ancor siede tremenda, ancor minaccia
a lui strage ed ai figli ed agli averi
lor poverelli. E spesso
il meschino in sul tetto
dell'ostel villereccio, alla vagante
aura giacendo tutta notte insonne
e balzando più volte, esplora il corso
del temuto bollor, che si riversa
dall'inesausto grembo
su l'arenoso dorso, a cui riluce
di Capri la marina
e di Napoli il porto e Mergellina.

Leopardi (1798-1837), La Ginestra.

Men argue, Nature acts.

Voltaire (1694-1778)

Nature knows no pause in progress and development,
and attaches her curse to all inaction.

Goethe (1749-1832)

The man is only half himself, the other half is his expression.

Emerson (1803-1882)

Preface

The purpose of this report is to present a variety of research objectives directed toward a better understanding of Vesuvius for the purpose of avoiding volcanic hazard to populations in the Vesuvian area. To accomplish this objective it is proposed to develop a global volcanic simulator for Vesuvius by means of which the hazard-zonation maps of future volcanic events can be produced and the populations in the Vesuvian area can be educated about the impending danger of the sleeping giant. The research needs aimed at the development of a simulator described in the report involve interdisciplinary efforts in volcanology, geology, geophysics, petrology, mathematical and physical modeling, and computer sciences. The development of a global volcanic simulator for Vesuvius requires a considerable increase in the quality of future research which can and must be realized before the giant awakes from its hibernation.

In preparing this report I wish to express my sincere thanks to Agnese Bilanceri who drew figures for the report, Paolo Papale for his help with some of the material in sections 2 and 3 dealing with the volcanological studies, Raffaello Trigila and his co-workers C. Romano, A. De Benedetti, and C. Freda for providing most of the material for section 5 dealing with the thermodynamic parametrization studies of magmas, and to Juan I. Ramos for critical reading, useful comments, and parts of the material of section 6 dealing with physical, mathematical, and computer modeling research requirements. I also wish to thank F. Barberi and G. Macedonio for critical reading and contributions, and S. Coniglio, G. Giordano, L. Marinoni, A. Neri, and M. Todesco for their support and contributions.

The global simulation of Vesuvius requires efforts which parallel those of the grand challenges of the 1990s: climate modeling and ocean circulation; fluid turbulence and viscous flow; quantum chromodynamics; and human genome. When I proposed the development of a global volcanic simulator for Vesuvius several years ago to the President of the National Volcanic Group of Italy Franco Barberi and indicated that this development requires visionaries to carry out its objectives, I was impressed by his immediate enthusiasm; I believed that there are many more like him. Since then, I began more and more to appreciate Machiavelli who declared:

E debbasi considerare come non è cosa piú difficile a trattare, né piú dubia a riuscire, né piú periculosa a maneggiare, che farsi capo a introdurre nuovi ordini; perché lo introduttore ha per nimici tutti quelli che degli ordini vecchi fanno bene, e ha tepidi defensori tutti quelli che degli ordini nuovi farebbono bene.

Pisa
April, 1993.

Flavio Dobran

Prologue

In 1990 the National Volcanic Group of Italy (GNV) submitted to the Minister of Protezione Civile a report entitled "Eruptive Scenario of Vesuvius". At that time, this report synthesized the available scientific information on Vesuvius and delineated a scenario of expected phenomena in the case of the reactivation of the vulcano which has been quiescent since 1944. The GNV report underlined the enormous potential for the volcanic risk of the entire Vesuvian area and solicited the Minister to adopt the necessary protection measures. In 1992 a commission formed by the Minister produced guidelines for the evaluation of volcanic risk associated with the Vesuvian area. The report of the commission established that there are about 700,000 persons who may be exposed to the risk, and which would therefore have to be evacuated *before* the initiation of an eruption. In particular, the report provided indications on the work which is still needed to be performed; from one end to affirm the existing knowledge and behavior of the volcano (precursor phenomena and expected eruption), and from the other end the preparation of emergency plans which are adequate to prevent the terrible crisis connected with an eruption in the Vesuvian area.

In 1993 GNV decided to promote a first three-year plan of research on Vesuvius (similarly for Etna and Vulcano) with the objective to obtain, through a multidisciplinary approach, that progress which is necessary for a true quantification of hazard of the volcano. Toward this end, GNV solicited a call for proposals and suggested the principal scientific problems for a three-year research program. The present report can be considered as an extension of this call for proposals in which the scientific community is summoned for an extraordinary and truly innovative effort to produce a global volcanic simulator for Vesuvius with a real predictive capability. The project is of vast breath and of enormous ambition. It sets the stage for an understanding and thus reproduction, modeling, and laboratory simulation of all fundamental processes which govern the functioning of the vulcano; from the genesis of magma, magma segregation, ascent and differentiation in magma chamber, all the way to the eruption and pyroclastic dispersion of products in the atmosphere. The principal merit of the report resides in identifying the necessary data which are required by the simulator, and the studies and technical and scientific approaches which are necessary and possible to obtain. The proposed project is very complex and difficult to realize, but not impossible and it is an objective worthy of pursuit.

The report will probably provoke discussions and certain points merit further elaborations. I wish that these discussions will be constructive and that the report will stimulate further constructive contributions. Each researcher has the duty to embrace the new, submit to the discussions his or her methods of research, and to take cognizance of new frontiers. This duty is multiplied for the volcanological community, from whose scientific validity depends the wellbeing of thousands of individuals. As for my part I pledge a maximum commitment until this extraordinary scientific adventure passes to its realization. Whatever the practical result we strive to reach, we have at least indicated the way to follow for the future generations of volcanologists.

Pisa
April, 1993.

Franco Barberi

CONTENTS

1. Introduction

"The Vesuvius has an elevated potential for territorial damage. The risk can, however, be mitigated and it can and it must be avoided that a natural event transforms into a national calamity." These words are the conclusion of the commission instituted by the Dipartimento della Protezione Civile (Italy) to define guidelines for evaluation of risk associated with volcanic eruptions in the Vesuvian area (GNV, 1992). In order to define these guidelines, this commission, henceforth referred to as *the Commission*, found it necessary to delineate the characteristics of a *reference event* which was assumed to correspond to a subplinian volcanic eruption of Vesuvius taking place within the next 20 years. This reference event was chosen on the basis of the past eruption history of Vesuvius.

A subplinian volcanic eruption of Vesuvius spells a doomsday scenario for about 700,000 people who live and work on the flanks of the cone or in the immediate surroundings of Vesuvius. The subplinian eruption of Vesuvius in 1631 is a possible reference event, as identified by the Commission, which produced plinian eruption column, column collapse precipitated by the caldera collapse which generated pyroclastic flows and surges, rainstorms and lahars, and destroyed the neighboring towns of Torre del Greco, Torre Annunziata, and part of Herculaneum (Rosi et al., 1992). The volcanic risk in the Vesuvian area is aggravated by congestion and urbanization with 18 communities being possibly exposed to an eruption. Herculaneum, Ottaviano, Torre Annunziata and Torre del Greco may require an evacuation of more than 250,000 people and 300 km^2 may be exposed to high ash loading rates which can produce roof collapses. Such an evacuation can be a nightmare unless it is properly planned and executed on time.

Based on the reference event of a subplinian eruption, the Commission set forth to define intervention plans and identify volcanic risk based on the properties of such an eruption, expected damage, eruption precursors, and seismic episodes. The report of the Commission states that the definition of the reference event, or expected eruption in the next 20 years, is based on a solid scientific basis. The AD 79 eruption type was excluded from the scenario of near-term possibilities and a high (not quantified) probability was given instead to subplinian eruptions. The Commission defined the research objectives as being the identification of event parameters and description of reference scenarios which include the meteorological conditions, height of eruption column, and duration and modalities of the eruption. The physical characteristics of the reference event were identified as being the fallout of ash, lapilli, and bombs from eruption clouds, pyroclastic flows and surges along the flanks of the cone, mud flows along the incisions and valleys of the volcano, lahars generated from condensation of steam in the eruption clouds or from emptying of underground aquifers, releases of toxic gases such as CO_2, CO, SO_2, *etc.* The expected damage to humans and property due to lithic projectiles, pyroclastic flows and surges, lahars, *etc.*, was also placed into perspective for further study. The long-, near-, and short-term eruption precursors to the expected eruption were also identified and a need to relate these precursors to impending eruption was stressed.

The evaluation of a volcanic *risk*, or the possibility of a loss - such as life, property, productive capacity, *etc.* - within the area subject to the hazard(s), is based on the knowledge of hazard, vulnerability, and value (Tilling, 1989a). *Hazard* is the probability of a given area being affected by potentially destructive volcanic processes or products within a given period of time; *value* may include the number of lives, property and civil works; and *vulnerability* is a measure of the proportion of value likely to be lost in a given hazardous event. The Commission identified three hazard zones at Vesuvius for each (unidentified) physical parameter. These zones are described in terms of the adjectives intense, rapid, large, concentrated, devastating, marginal, *etc.* In order to assess vulnerability and risk, the Commission identified a need to produce databases of physical state of the Vesuvian area, distribution of population and activities, structures, mobilities of persons, functioning of emergency plans, *etc.* The hazard, value, and vulnerability parameters need to be subsequently combined to produce a volcanic risk assessment for the Vesuvian area in terms of maps or graphs which show spatial and temporal distributions. As strategies for risk containment, the Commission defined the necessity to evade further aggravation of urbanization near the volcano, reclaiming of urban areas to decrease risk, invitation to the participation of all civil protection structures in risk mitigation, and an operational structure on the territory consisting of an educated population who knows how to confront the emergency.

The above summary of the Commission's report sets a precedent for further and very difficult work dealing with quantification and preparation of *operational plans* for the Vesuvian area. The reference volcanic event identified from past eruptions of Vesuvius defined by the Commission is necessary, but it is not sufficient, to serve as a basis for producing the hazard-zonation maps, since volcanoes do not always and closely follow past eruptive behavior. The catastrophic events can exceed known precedents at the same volcano (Crandell et al., 1984) with an example being the recent eruption of Mt. St. Helens on May 18, 1980. The blast at this volcano extended about three times further from the volcano than the largest known previous blast at Mt. St. Helens, and it affected an area more than 10 times larger (Miller et al., 1981). A volcano can change shape, and consequently alter the likelihood of areas being affected by various events. The growth of a volcano can fill valleys and thereby direct pyroclastic flows and lahars down previously unaffected valleys. It may also be dangerous to use the precursory seismicity from past volcanic eruptions to produce future risk assessment, since for both an eruption and magma intrusion, the length of time of the associated seismicity can vary widely from volcano to volcano and from eruption to eruption at the same volcano (Banks et al., 1989). Some precursory seismicity leads eruptions by a year or more (the eruptions of Krakatau in 1883 and Nevado del Ruìz in 1985), but most lead times vary from weeks to months (from March to May at Mt. St. Helens). The precursory seismicity preceding the eruptions of Krafla in Iceland in 1975 and most eruptions of Kilauea in Hawaii began a few days or hours before the eruptions (Banks et al., 1989). Prior to the 1631 eruption of Vesuvius on December 16, the ground tremors were heard only 6 days before the devastating subplinian event (Rosi et al., 1992).

An effective program to mitigate volcanic hazard and risk must be built on a strong foundation (Fig. 1) with the scientific community providing a sound knowledge base. The geologic and geophysical mapping, petrological and geochemical characterization of eruptive products, dating of stratigraphically well-controlled samples, and physical modeling of eruptive processes must be well integrated in order to assess volcanic hazard (Fig. 2). A comprehensive understanding of eruptive phenomena and eruption frequency is the starting point for mitigation of volcanic risk (Tilling, 1989a). The complete record of historical eruptions, prehistoric eruptive activity deduced from the geological record, geological, petrological, and geochemical data on the nature, distribution and volume of the eruptive products, and dating of the volcanic products and events interpreted from them, are essential data needed for adequate hazard assessment (Crandell et al., 1984). The hazard assessment and zonation, volcano monitoring, and volcanic emergency management form part of any effective program to mitigate the volcanic risk as clearly identified by the Commission. All of these tasks are very complex to realize, and past eruptions of Vesuvius provide an excellent guide for inferring the future eruption styles and testing of scientific models. This does not imply, however, that we should employ only past eruption data to "predict" future eruptions of Vesuvius. This approach would have a too narrow scientific scope and it would not serve the best interests of the population surrounding the Vesuvian area, and certainly it would not do justice to the *potential* scientific methods for assessing the volcanic risk at Vesuvius.

From the above considerations, it is clear that the determination of volcanic risk at Vesuvius should be based on an interdisciplinary scientific model which must be tested on past eruptions. Such a *global volcanic simulator* (Dobran et al., 1990; Dobran, 1991b) could be used to establish probabilistic hazard maps and an assessment of vulnerability to the population in the Vesuvian area. The volcanic hazard-zonation maps should delimit the zones of hazard related to *each type of event*, such as due to tephra fallout, lava flows, pyroclastic flows, lateraly directed blasts, debris avalanches and lahars, volcanic gases, tsunamis, *etc.* Figure 2 from the Commission's report (GNV, 1992) represents in effect a model of a volcanic simulator since it consists of most of its essential ingredients. What is lacking

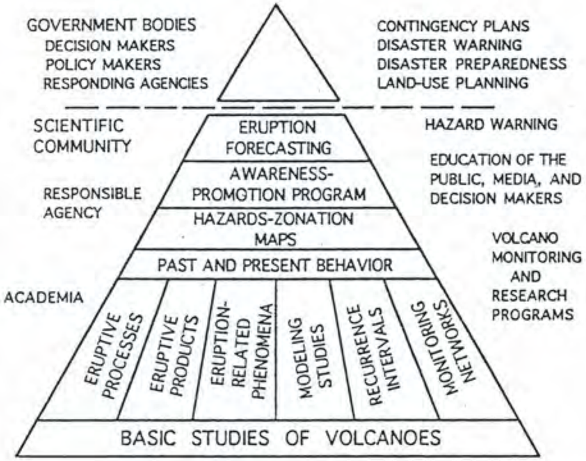

Figure 1. Diagram illustrating the building blocks of a program for mitigation of volcanic risk. The apex is separated from rest of triangle to indicate the division of primary responsibility between the scientists and civil authorities (Tilling, 1989a).

in the report, however, is a description of how this simulator can be actually constructed and of how it can be used to establish the hazard-zonation maps. This aspect of the problem is illustrated in Figure 3 (Dobran, 1991b) and involves the incorporation of volcanological, geophysical, and other data in producing physical models of different volcanic processes which are subsequently combined into a simulator for implementation on a computer. This computer program can then be used to produce different eruption scenarios that can in turn be used to generate hazard-zonation maps. It should be noted that a simulator must be able to reproduce past eruptions and that for this purpose these eruptions or *test cases* must be well defined from volcanological, petrological, and geophysical data bases.

The prediction of volcanic eruptions by a simulator critically depends on its capability to simulate past eruptions or reference events as defined by the Commission. To simulate the 1631 eruption of Vesuvius, for example, the simulator would have to predict the magma ascent, formation of a plinian column, caldera collapse, column collapse and generation of pyroclastic flows in different valleys of the volcano, and production of lahars from condensation of steam in the eruption column or from magma-water interactions taking place during caldera collapse when the aquifers were emptied. A global volcanic simulator for Vesuvius should be able to simulate magma supply and differentiation at depth during long repose times of the volcano, and the plinian, subplinian, and strombolian events with

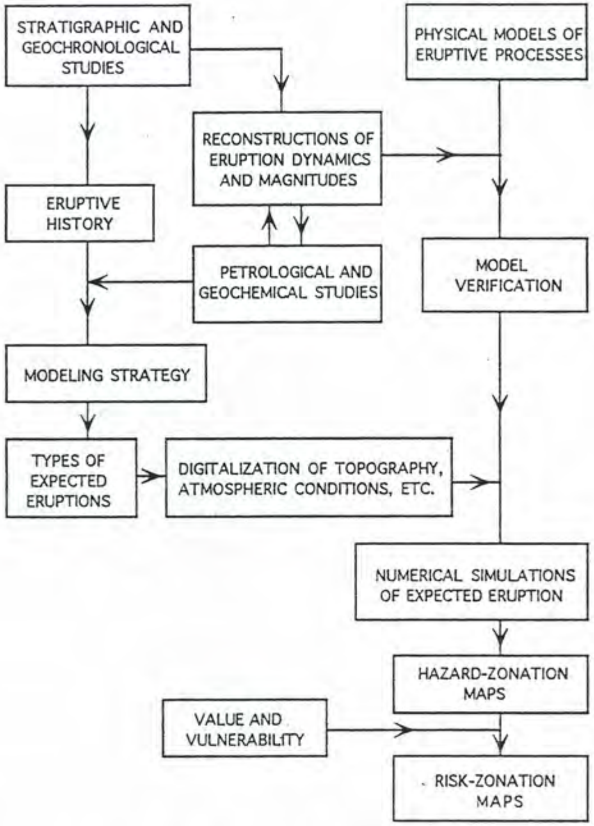

Figure 2. An approach suggested by the Commission (GNV, 1992) to produce hazard-zonation maps for Vesuvius.

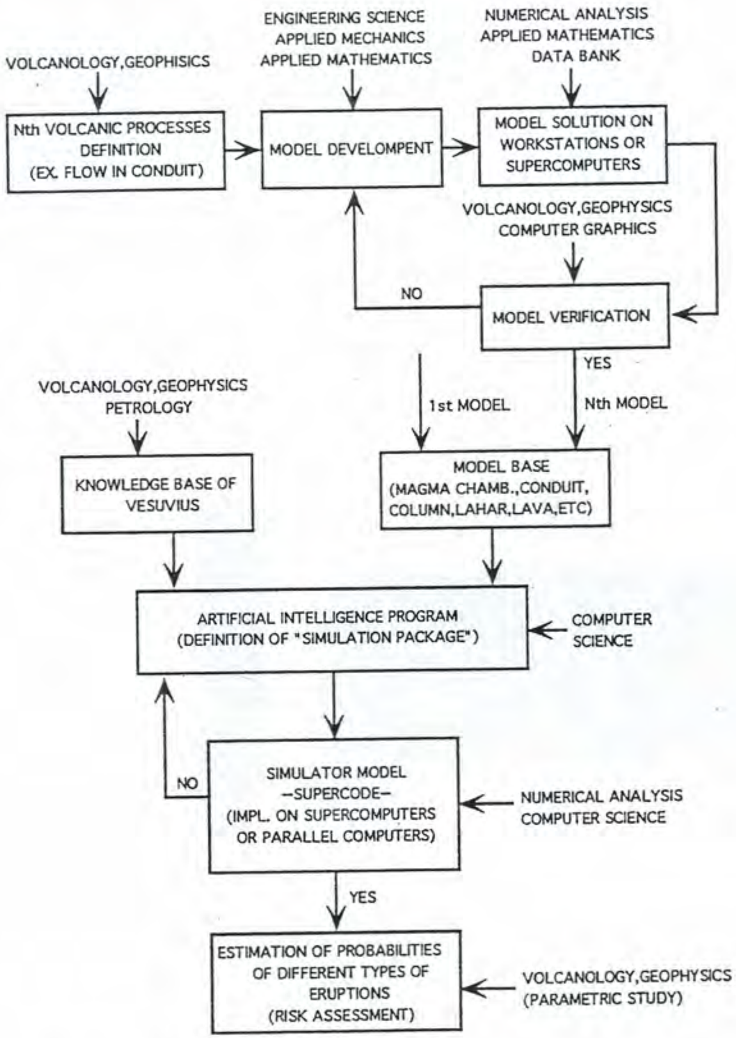

Figure 3. Global volcanic simulator development stages (Dobran, 1991b).

lava flows during the eruptions.

The objective of this report is to define the research which is needed to develop a global volcanic simulator for Vesuvius in order to use this simulator to establish hazard-zonation maps for the Vesuvian area. Section 2 of the report summarizes the past eruptions of Vesuvius and inferred functioning of the volcano, and defines the test cases or reference eruptions needed to test the simulator. Section 3 places in perspective the petrological, volcanological, and geological research needs pertaining to reference events. The understanding of the present functioning of Vesuvius is crucial and section 4 discusses the required geophysical research objectives aimed at a better understanding of the present state of the volcanic complex. The thermodynamic and petrologic parametric studies required to define "future" magma composition(s) and the effect of kinetics on composition(s) is discussed in section 5. Section 6 defines the physical, mathematical, and computer modeling research requirements and the associated systems integration procedure studies. The parametric studies and procedures required to produce hazard-zonation maps are discussed in section 7.

2. The Vesuvian Volcanic Complex

2.1 Morphology

The convergence of the Eurasian and African plates is responsible for seismic and volcanic activities in the central and southern parts of Italy (Principe et al., 1987). The Vesuvian region includes the Somma-Vesuvius volcanic complex and is located between the opening Tyrrhenian basin to the west and the westward-migrating Apennine compressive front to the east. A schematic representation of the main stratigraphic and structural units of the Campanian region is shown in Fig. 4 (Ippolito et al., 1973). The volcanoes in this region of Italy are related to an extensive faulting which displays two main trends: one parallel (NW-SE) and the other normal (NE-SW) to the main axis of the Apennines. The Somma-Vesuvius and Phlegraean Fields are within or nearby these faults. The Phlegraean Fields is a caldera located about 30 km to the west of Somma-Vesuvius, whereas the volcanic islands of Ischia and Procida lie at the mouth of the Bay of Naples, Roccamonfina 60 km to the northwest, and Vulture 100 km to the east (Fig. 4). The volcanic activity apparently started at Roccamonfina about 600,000 years ago (Ballini et al., 1989), 50,000 years ago at Phlegraean Fields, and 300,000 years ago at Somma (Principe et al., 1982). A period of contemporaneous activity of the Campanian region volcanoes is estimated between 200,000 and 100,000 years ago (Principe et al., 1987). Historical eruptions are recorded at Ischia in 1301, Phlegraean Fields in 1198 and 1538, and Vesuvius from AD 79 to 1944 (Santacroce, ed., 1987).

Phlegraean Fields is represented by a 12 km wide caldera, resulting from the

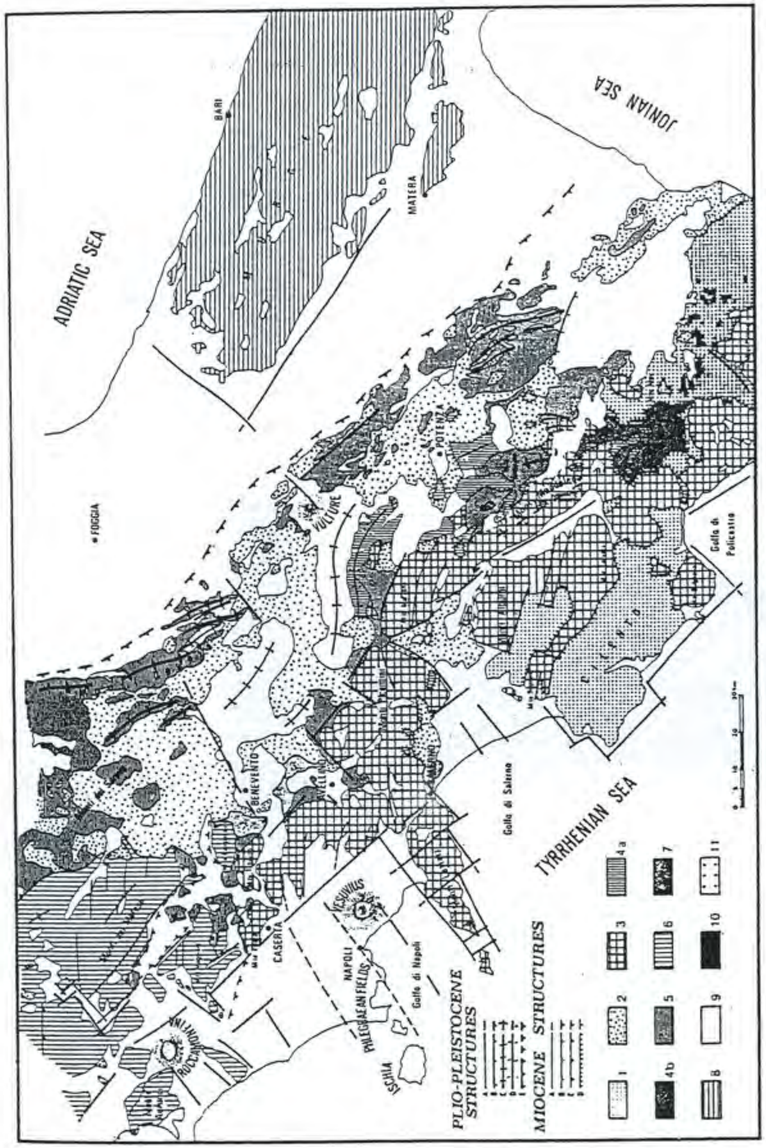

Figure 4. Geological map of the Campanian volcanic area (Ippolito et al., 1973).

collapse following the emplacement of the Campanian Ignimbrite about 35,000 years ago (Rosi et al., 1983) which has an estimated volume of about 80 km^3 of material (Thunnel et al., 1978). The termination of the Monte Somma's activity and the birth of Vesuvius is taken at about 17,000 years ago whereby a major plinian eruption caused the formation of Somma caldera (Delibrias et al., 1979). The most recent cone, Vesuvius, is built inside the Somma caldera and the two structures join along Valle del Gigante (a narrow semicircle whose floor is formed by the lava flows of several eruptions) (Fig. 5). This valley is bounded by Atrio del Cavallo to the West and Valle dell'Inferno to the East. Vesuvius is a cone-shaped stratovolcano with a summit crater about 450 m in diameter and 330 m deep (Principe at al., 1987). The rim of the crater is asymmetrical, being steeper at its northeastern part than in its southeastern one, and the surface of the cone is interrupted by eccentric vents. The western part of Vesuvius flattens at about 500 m height into Piano delle Ginestre. The outer rim of this structure corresponds to the older caldera border which is almost completely destroyed by the overflowed post-caldera lavas.

2.2 Overview of Past Eruptions of Vesuvius

The lavas found at a depth of 1345 m (1125 b.s.l.) at the geothermal well drilled at the southern slopes of Vesuvius (Balducci et al., 1985) have been dated as being about 300,000 years old, but the eruption field data date back to about 25,000 years (Principe et al., 1987). During the past 25,000 years Vesuvius has displayed a complete spectrum of activity, ranging from effusive lava flows to explosive plinian eruptions (Arnó et al., 1987). Figure 6 illustrates the general eruptive sequence of Somma-Vesuvius, with Fig. 6b illustrating the most recent activities of Vesuvius. According to Arnó et al. (1987) and Civetta and Santacroce (1992), the last 25,000 years of activity at Vesuvius can be characterized by three main magmatic cycles. The oldest cycle from 25,000-11,500 BP (Before Present) is characterized by the emission of slightly undersaturated lavas (K-basalt to K-latite) and pyroclasts (K-latite to K-trachyte), and was dominated by 3 or 4 plinian eruptions which were preceded by several centuries of repose and alternated with lava effusions and, possibly, minor explosive events. The intermediate cycle from 7,900 BP to AD 79 is characterized by three plinian eruptions (Mercato, Avellino, Pompei), long repose periods, and several subplinian and minor events. The magma composition in these eruptions ranges from tephrite to phonolite. The youngest cycle of activities, from AD 79 to the last eruption in 1944, was characterized by the emission of leucititic-tephrites to phonolitic-leucitites, pointing to a progressive decrease with time of the silica saturation of erupted magmas. These activities range from subplinian eruptions in 472 and 1631 to strombolian and lava flow activities from 1631-1944. The plinian and subplinian eruptions can be characterized as the closed conduit condition erup-

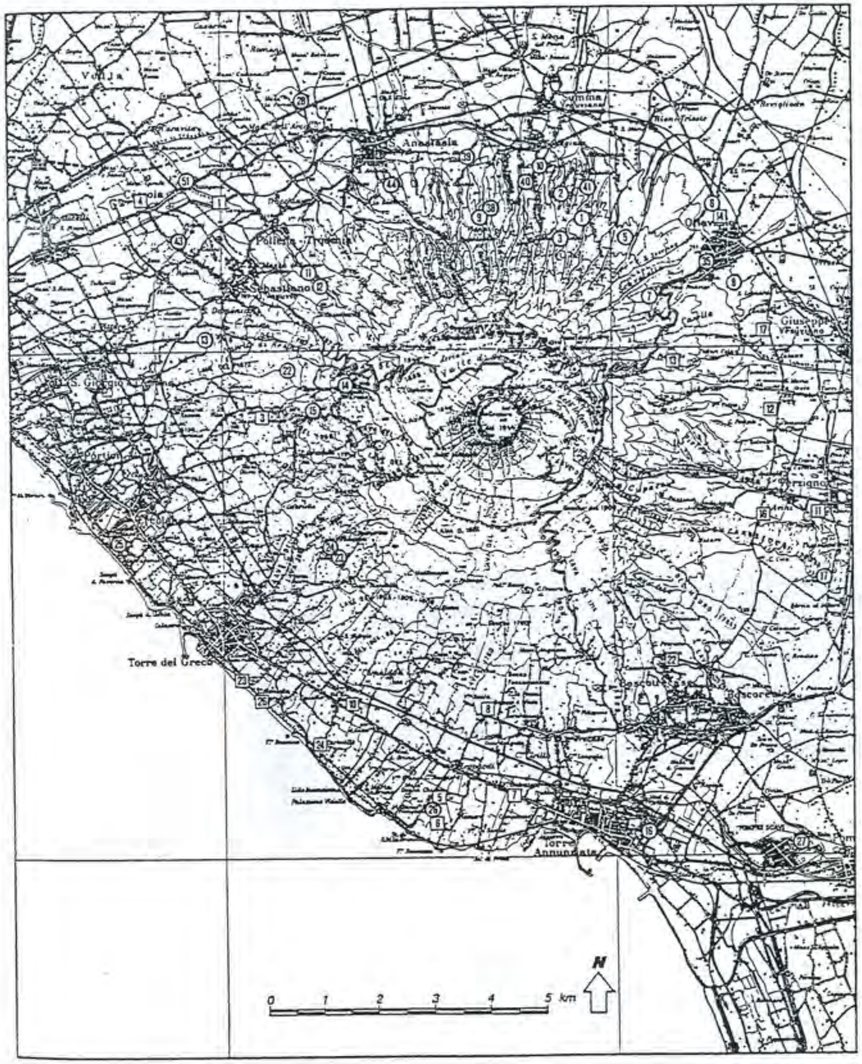

Figure 5. Topographic map of the Somma-Vesuvius area (Principe et al., 1987).

tions since they are believed to have occurred from a state when the conduit was closed. The strombolian and lava flow activities occurred from the open conduit condition. Figure 7 (Macedonio et al., 1990) shows the relationship between the fraction of primary liquid of emitted magma and repose periods preceding the last eruption for the last 10,000 years of activity at Vesuvius. The evolved compositions (trachytes and phonolites) displayed in the figure with fractions less than about 0.2 represent the large plinian eruptions, whereas the more primitive compositions (K-basalts and leucitites) belong to the less powerful eruptions of the strombolian and lava flow nature. From Figs. 6 and 7, it is evident that large plinian eruptions can exhibit very long repose times (hundreds to thousands of years), subplinian eruptions several hundred years, and strombolian and lava-flow eruptions on the order of a decade.

The plinian eruptions of Codola (about 25,000 years BP), Sarno (about 22,000 years BP), Basal (about 17,000 years BP), Greenish (about 15,500 years BP), Lagno Amendolare (about 11,400 years BP), Mercato (about 8,000 years BP), Avellino (about 3,800 years BP), and Pompei (AD 79) (Arnó et al., 1987) exhibit voluminous tephra deposits up to several cubic kilometers. The uncertain Codola eruption produced a white pumice-fall level that grades upward into a horizon with greenish pumice. The Sarno plinian products consist entirely of air fall pumice, ranging from white at the base to gray at the top. The Basal eruption exhibits a white-pumice fall deposit which is covered by a lapilli layer rich in lava and carbonate ejecta and followed by a sandwave surge deposit. The Greenish plinian eruption shows a fall-surge-fall sequence whereby the lower pumice-flow darkens upward due to an increasing lithic content. The Lagno Amendolare eruption does not appear to be accompanied by surge and pyroclastic flow deposits but exhibits only a white pumice (the color of which darkens upwards) fall. A voluminous pyroclastic sequence characterizes the Mercato plinian eruption, with the fall deposit typically consisting of two levels of white pumice which are often separated by a thin ash cloud surge deposit. A third pumice-fall level rich in lithic fragments also belongs to this eruption. The pumice fall and pyroclastic surge and flow deposit distributions of the Avellino plinian eruption are illustrated in Fig. 8. The deposit of this eruption shows an abrupt change in pumice color from white to gray roughly midway up the deposit and both layers contain abundant carbonate ejecta. The eruption apparently increased in vigor with time and the pyroclastic flow deposits are not common.

The AD 79 Pompei eruption of Vesuvius started at about 1 p.m. on April 24 with the formation of a plinian column that was preceded by a phreatomagmatic opening phase. For the following seven hours, a phonolitic magma (white pumice) was ejected. At about 8 p.m. on the same day, the magma composition changed to tephritic phonolite (gray pumice), and at 1 a.m. on August 25 several pyroclastic surges occurred, the first of which destroyed Herculaneum and the fourth of which

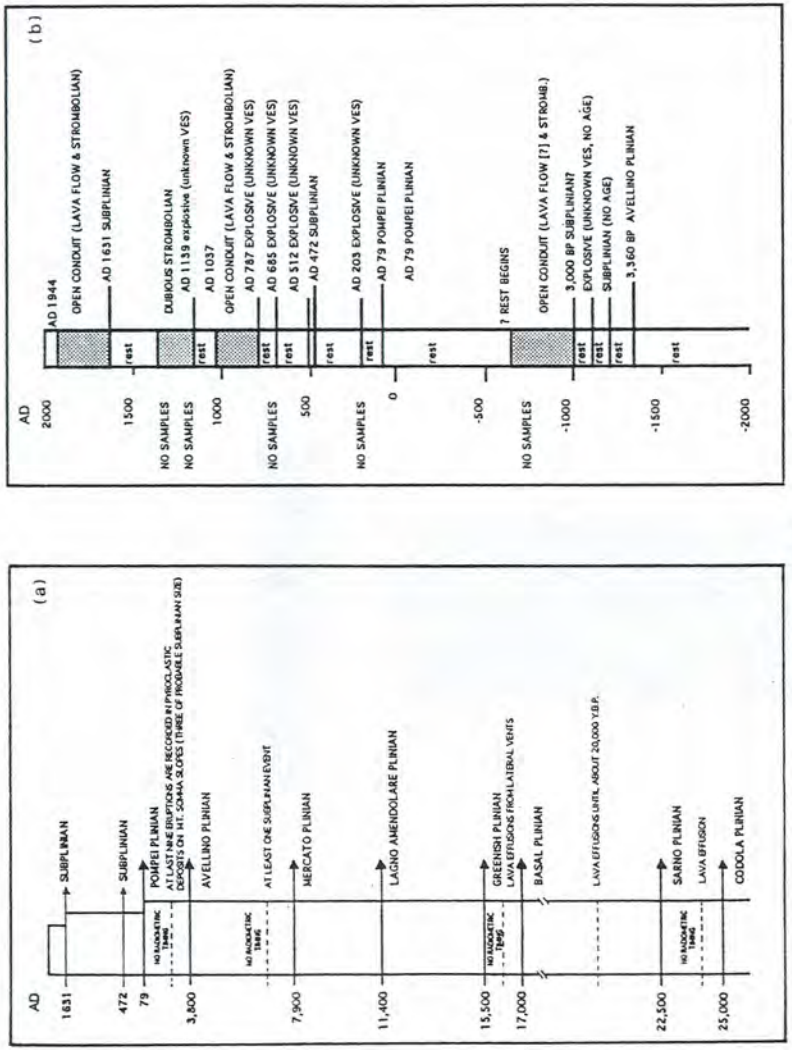

Figure 6. (a) General stratigraphic sequence of Somma-Vesuvius volcanic activity (Arnó et al., 1987). (b) The eruptive history of Vesuvius in the last 4000 years (as updated by Civetta and Santacroce, 1992).

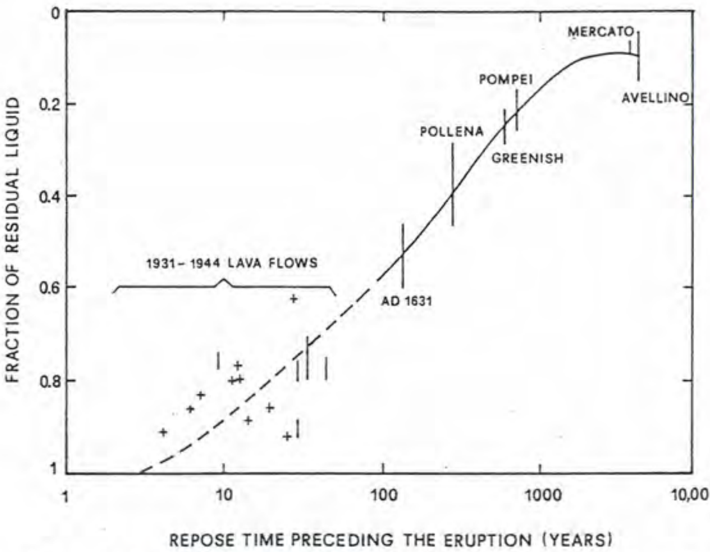

Figure 7. Degree of magma fractionation versus the repose time (Macedonio et al., 1990).

destroyed Pompei and killed about 2,000 people (Carey and Sigurdsson, 1987; Sigurdsson et al., 1982,1985,1990; Lirer et al., 1973, Barberi et al., 1981; Sheridan et al., 1981). The Pompei eruption discharged about 3 km^3 of material (Fig. 9). Following Barberi et al. (1989) and Civetta et al. (1991) four main phases of the AD 79 eruption can be distinguished: (1) a phreatomagmatic explosive opening, (2) a plinian phase which includes a fallout-derived white and gray pumice and the interbedded pyroclastic surges, (3) a "dry surge and flow" phase which is mainly characterized by the collapse of the eruptive column, and (4) a final "wet surge and flow" phase of phreatomagmatic origin. Figure 9 illustrates the isopachs of the airfall and pyroclastic flow and surge deposits of the Pompei eruption.

The 472 Pollena subplinian eruption exhibited a sequence typical of the major Vesuvian plinian eruptions, but discharging a significantly lower volume. The eruption is characterized by plinian pumice-fall, increasing carbonate and lava ejecta, *nueè-ardent* flow, and wet pyroclastic flows which indicates an increasing hydromagmatic character. Figure 10 illustrates the isopachs of air-fall and pyroclastic-flow and surge deposits of the Pollena eruption.

The 1631 eruption of Vesuvius was the most destructive event in the recent history of this volcano (Rosi et al., 1992). On December 16 at 6:30 a.m., the eruption started with the ejection of gas and ash, and by 10 a.m. it produced a

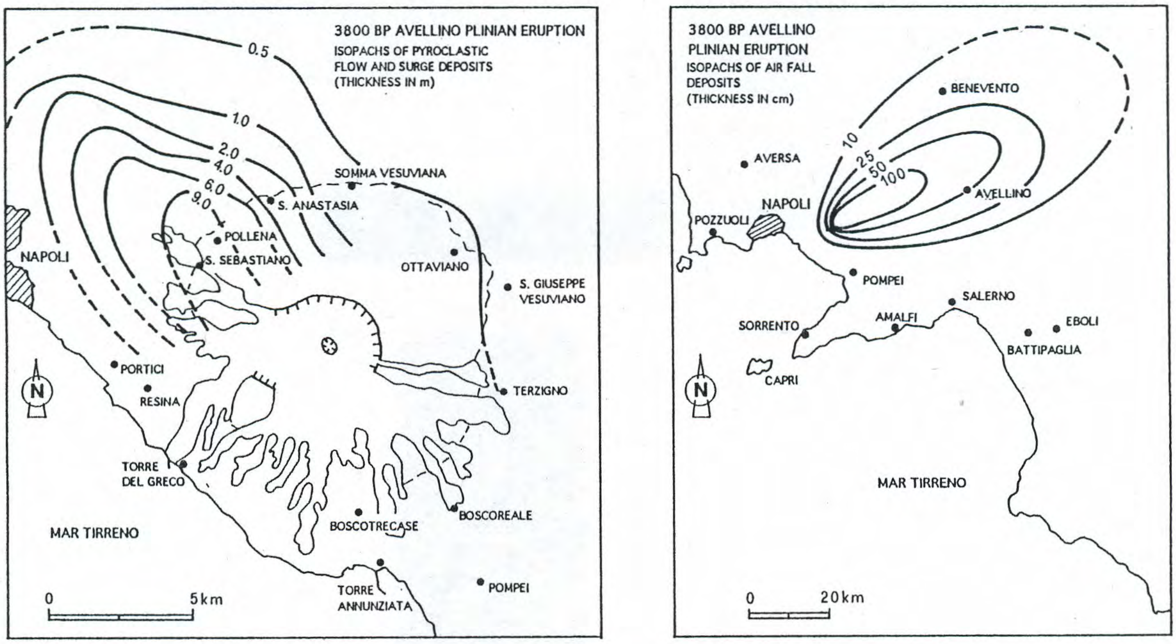

Figure 8. The 3800 BP Avellino eruption deposits. Isopachs of pyroclastic flow and surge, and of air fall deposits (Principe et al., 1987).

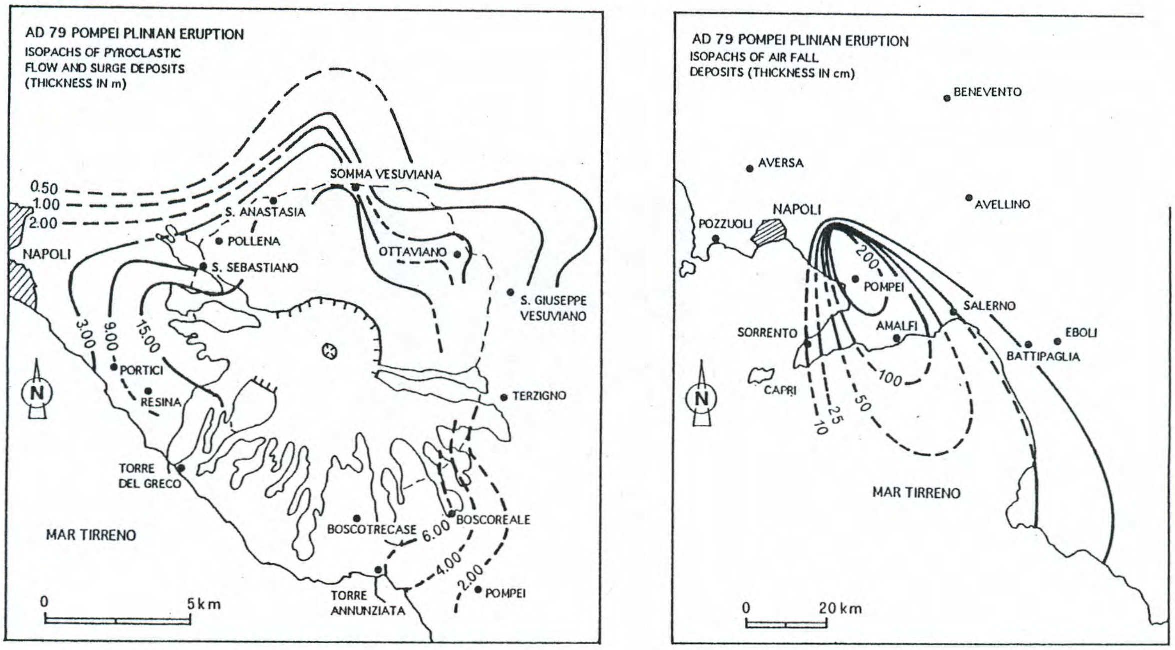

Figure 9. The AD 79 Pompei plinian eruption deposits. Isopachs of pyroclastic flow and surge, and of air fall deposits (Rosi et al., 1987).

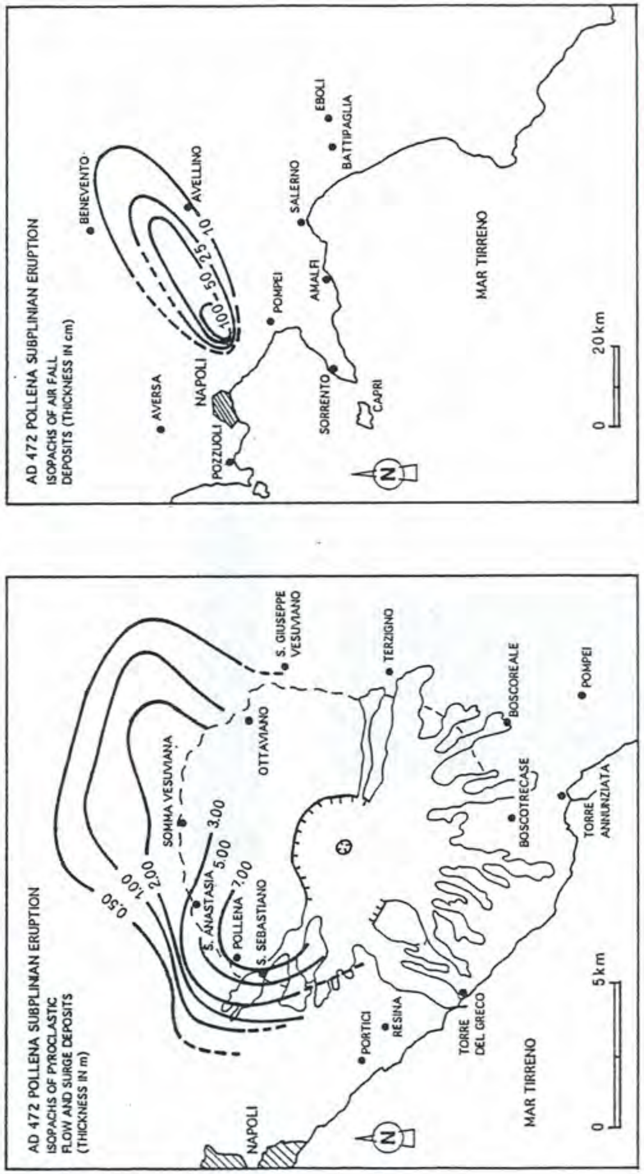

Figure 10. The 472 Pollena plinian eruption deposits. Isopachs of pyroclastic flow and surge, and of air fall deposits (Rosi et al., 1987).

plinian column. Between 7 and 10 p.m. on the same day, the eruption produced a succession of seismic shocks, and by 2 a.m. on December 17 a glowing cloud was seen issuing from the summit crater, flowing into the valley between the cone of Vesuvius and Mt. Somma. During the night, lahars were also seen coming down from the northern slopes of Mt. Somma, devastating the lands around Ottaviano. At 11 a.m., a violent earthquake occurred and the central crater was seen discharging ash, gas, and stones which poured down the slopes of the cone of Vesuvius. These *nueé-ardentes* descending from the mountain in lobes are described as being apocalyptic and upon reaching the sea produced tsunamis from 2-5 m high. They also destroyed Torre Annunziata 7.5 km and Torre del Greco 8.5 km away from the crater. In the evening of December 17 Vesuvius was forming new light-colored clouds, and persistent heavy rains during the days following the eruption were observed. The eruption produced decapitation of the cone by about 500 m and about 4,000 deaths, primarily because of the *nueé-ardentes.* Extensive destructions were suffered in Ottaviano, Massa di Somma, San Sebastiano, San Giorgio, and other places, and about 500 km^2 were covered by ash which destroyed crops, vineyards, and cattle.

The general stratigraphic succession of the 1631 eruption shows, from base to top, a main plinian fallout, fallout of blocks and ash, upper lithic-rich fallout, ash and surge, and fine-grained phreatomagmatic ash (Rosi et al., 1992). Figure 11 illustrates the isopachs of the plinian fallout produced by the eastward blowing wind. The upper lithic-rich fallout suggests sustained steam blasts during the night between 16 and 17 of December. The ash flow and surge eruption phase occurred during extensive cratering and produced *nueé-ardentes* and beheading of the cone of Vesuvius. The phreatomagmatic phase following the *nueé-ardentes* is associated with the emptying of aquifers as caused by the caldera and conduit wall collapses which brought about a collapse of the plinian column and generation of pyroclastic flows. The 1631 eruption discharged about 0.2 km^3 of material and its tephritic-phonolitic magma composition varies from more differentiated (producing white pumice) to more primitive (producing darker pumice). This eruption is important since it represents a good reference event or test case which can be used to test the simulator. It had a great impact on the populated areas surrounding Vesuvius and caused extensive damage and fatalities. The macroscopic precursors felt by the population began only a week before the eruption, and the eruption reached a (destructive) climax within 48 hours.

Between 1631 and 1944 at least 18 eruptive cycles, frequently interrupted by violent explosive-effusive eruptions, have been identified (Arnó et al., 1987). Within each cycle, the effusive eruptions (intermediate eruptions) were frequent and the more voluminous and mostly explosive eruptions (final eruptions) systematically closed the cycles. Santacroce (1983) related the intermediate eruptions to the arrival of magma into the volcanic system of Vesuvius, whereas the final eruptions

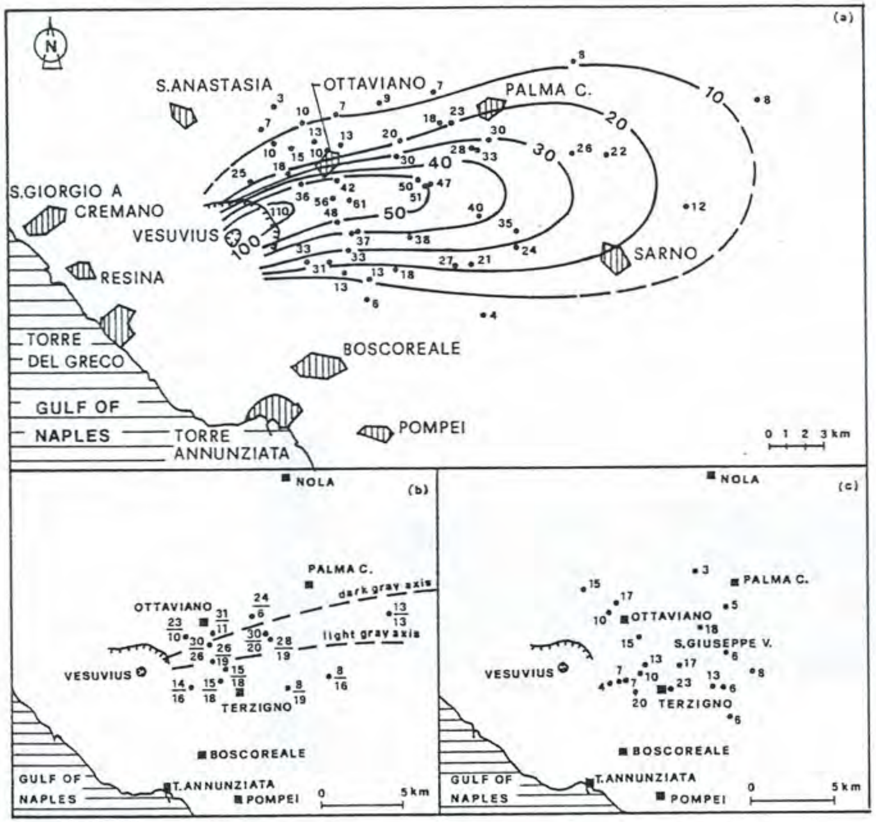

Figure 11. The 1631 subplinian eruption deposits. (a) Isopachs of air fall deposits in cm. (b) Isopachs of pyroclastic flow and surge deposits in cm. (c) Thickness of phreatomagmatic ash in cm (Rosi et al., 1992).

were interpreted as emptying of the plumbing system of Vesuvius. The April 1906 eruption of Vesuvius is an example of the final eruptions and ends the 17th eruptive cycle (Fig. 12) (Santacroce et al., 1992) which spans the years 1874-1906. The cycle began on January 1874 with the resumption of strombolian activity at the central crater. During the following years, the volcano was characterized by a semi-continuous production of lava (Colle Margherita (1891-1893), Colle Umberto (1895-1899)) from several lateral vents and fractures located between 750 and 900 m altitude. The cycle ended with the April 4 eruption in 1906 with the opening of a system of fractures and vents between 1200 and 600 m elevation at the southern slopes of the cone (Mercalli, 1906; Perret, 1924; Bertagnini et al., 1991) as shown in Fig. 13. Between April 4 and 6 (1st phase), the lava was emitted from vents at progressively lower elevations. In the early afternoon of April 7 (beginning of 2nd phase) the activity at the central crater intensified with repeated explosions and by about 10 p.m. on the same day the lava fountains reached heights of 1-2 km above the crater. The lava fountains reached their climax in the night of April 7 and 8 with spectacular resumption of the effusive activity from a new vent (no. 4 in Fig. 13) and from other existing vents (see Fig. 13). At 3:30 a.m. on April 8 (beginning of 3rd phase), the eruption dynamics changed by the formation of fountain activity and shattering of the cone of Vesuvius. This event followed with the production of an eruptive column which was estimated to be 13 km high (Perret, 1924) and lasted until the morning of April 9. After this time (beginning of 4th phase), low eruptive clouds continued to rise above the central crater, and by April 21 the eruption was over. Bertagnini et al. (1991) interpreted the shattering of the cone on April 8 as due to the flashing of a geothermal system surrounding the volcanic conduit of Vesuvius as caused by the drawdown of the magma column in conduit at about 3:30 a.m. on April 8. Magma lowering in the conduit is also assumed to have taken place during the 1st phase when the effusive vents opened at progressively lower altitudes (from 1200-600 m), and twice during the course of the 2nd phase.

The April 1906 eruption of Vesuvius producing lava flows, lava fountaining, gas-pyroclasts columns, and magma-water interactions is considerably different from the plinian and subplinian eruptions of Vesuvius. As such, this eruption should also be considered as a good reference event or test case to test the simulator, since an eruption of this nature in the future may produce a great deal of panic among the population, and possibly extensive damage and deaths to the urban centers located on the flanks of Vesuvius.

The above overview of the eruptions of Vesuvius was purposely contained in order to minimize speculations of different physical processes which may have been responsible for the rich collection of eruption styles. Based on the descriptions of eruptions in this section and further volcanological, petrological, geochemical, and radioisotopic data, in the following section an attempt will be made to infer

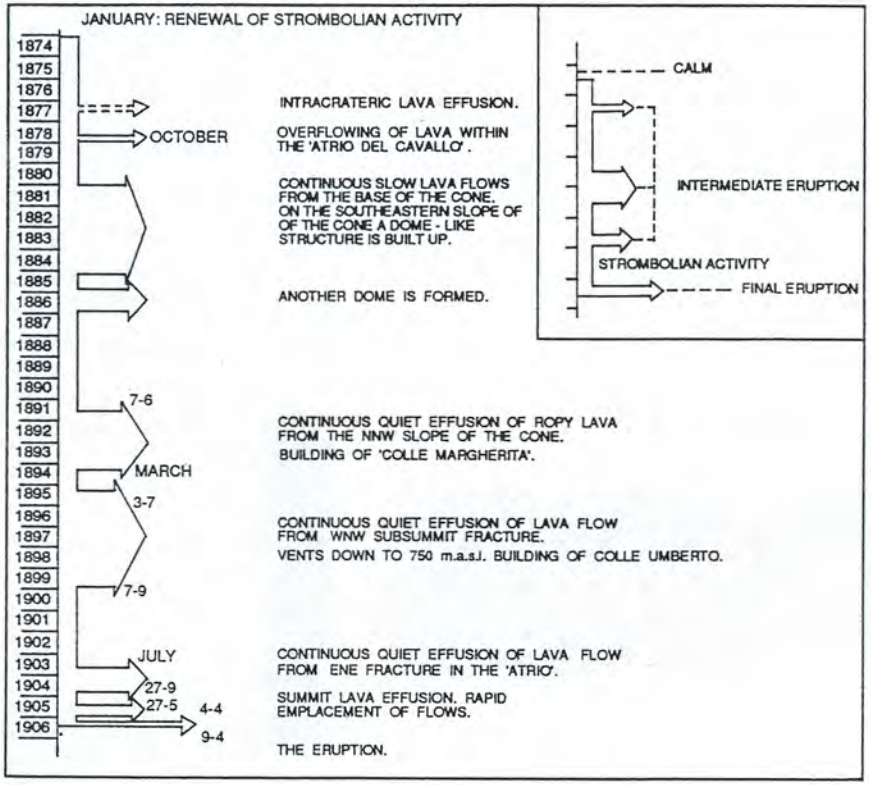

Figure 12. The 17th cycle of the recent activity of Vesuvius (modified by Santacroce et al., 1992; from Arnó et al., 1987).

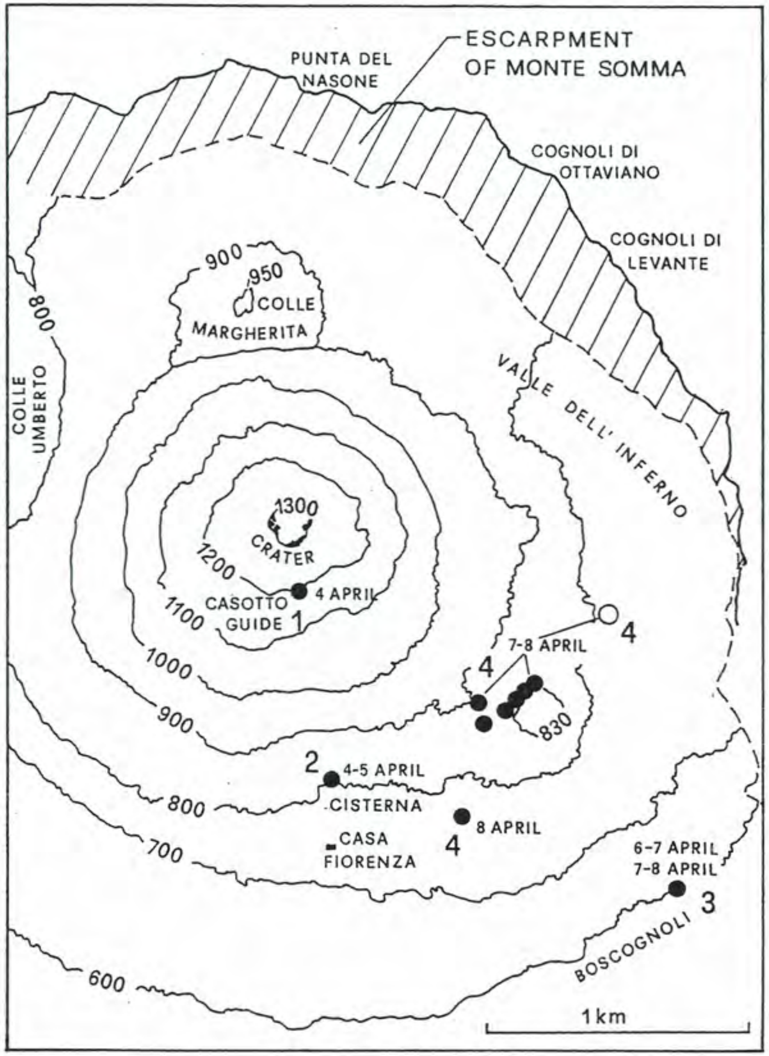

Figure 13. Location and date of opening of effusive vents during the 1906 eruption (Bertagnini et al., 1991).

the functioning of the volcanic system of Vesuvius.

2.3 Inferred Functioning of the Volcano

2.3.1 Volcanological and Petrological Results

As shown in Fig. 7, the large-scale catastrophic plinian eruptions of Vesuvius followed long quiescent periods exceeding several centuries or millennia (Avellino, Mercato, Pompei) and erupted large volumes of material (several km^3). The intermediate-scale subplinian eruptions (Pollena, 1631) occurred every few centuries and erupted about 0.1 km^3 of material. The smaller-scale strombolian and effusive events erupted about 0.01 km^3 of material. A common feature of the plinian eruptions is that they were subsequently interrupted due to partial column collapses producing pyroclastic surges and flows (Sheridan et al., 1981; Sigurdsson et al., 1985), and terminated with the interaction of magma with water from underground aquifers (Sheridan et al., 1981; Barberi et al., 1988,1989). Magma-water interaction also occured during the subplinian and strombolian eruptions in 1631 and 1906, respectively.

The Avellino to 1631 plinian and subplinian eruptions are all characterized by the emission of highly differentiated magmas, trachytic or phonolitic in character. The deposits contain limestones, various thermometamorphosed marble and skarn lithic ejecta which suggest the location of the magma chamber and/or magma fragmentation levels within the Mesozoic carbonate basement between 3 and 5 km below the volcano (Santacroce, ed., 1987). The pumice-fall deposits of Avellino, Pompei, and 1631 eruptions consist of white phonolite at the base and gray tephritic phonolite at the top (Rosi et al., 1987,1992). The subplinian deposits do not contain carbonate lithic ejecta, suggesting that the magma reservoirs or fragmentation levels were located *above* the Mesozoic carbonate basement (Civetta and Santacroce, 1992). Although the subplinian eruptions exhibit large compositional variations, the degree of magma evolution is smaller than that typical of plinian products, and no data appear to be available regarding the variation with time of the primary Vesuvian magma (Civetta and Santacroce, 1992).

Civetta et al. (1991) and Civetta and Santacroce (1992) discuss the functioning of the Vesuvian magmatic system based on petrological, geochemical, and isotopic data of volcanic products erupted during the last 3,400 years (from the Avellino eruption to 1944). Figure 14 shows the magma compositions for plinian, subplinian, strombolian, and effusive eruptions from about 3,400 BP to 1944 which demonstrate a complex history of the volcano. Each eruption style is nevertheless characterized by a peculiar composition. The pumice fall deposits of the Avellino and Pompei eruptions show a compositional variation from white phonolite at the base to gray tephritic phonolite at the top. These pumices have distinct Sr- and Rb-isotopic compositions and the two eruptions exhibit an opposite isotopic pattern (Fig. 15). The white Pompei pumice is more radiogenic than the white Avellino pumice, whereas the gray Pompei pumice is less radiogenic than the gray Avellino pumice. Whereas the white pumices of both eruptions display a range of ^{87}Sr/^{86}Sr ratios, the gray pumices have nearly constant ratios. When the Sr-isotopic ratios of pyroclasts from several eruptions from Sarno to the present are considered on the same plot (Fig. 16), they all exhibit significant isotopic and chemical variations. In each eruption, the more evolved products are ejected first, and it appears that the last-erupted or less-evolved magma of the older eruptive event has a Sr-isotopic ratio close to that of the first-erupted or more-evolved magma of the successive younger event. The lava flows from 1631-1944 have a decreasing Sr-isotopic ratio with time. The 1906 eruption exhibits, however, large petrochemical and isotopic variability whose Sr-isotopic range encompasses the whole variability of the Vesuvian products, as illustrated in Fig. 17. Santacroce et al. (1992) suggest that the 1906 eruption involved three different compositionally zoned magma bodies (A,B,C). A and B magmas were explosively ejected one after the other during the first phases of the eruption, whereas the C magma body was erupted as both lava flows and tephra during the main and final phases of the eruption and represented about 90% of the erupted mass. The A magma body has a nearly homogeneous isotopic imprint, low phenocryst content (about 25 wt%), and a large compositional variation (Santacroce et al., 1992). The B magma body reveals marked compositional zonations in both phenocryst content and glass inclusions. The C magma body contains large proportions of crystals, whose fraction increased during the eruption, it is isotopically homogeneous, and it has a low volatile content as deduced from low to moderate vesiculation of the ejected lapilli. The presence of water at different levels of the volcanic system of Vesuvius is consistent with many eruptions, and different aquifers appear to have been activated depending on the eruptive style.

2.3.2 Geophysical Results

The geophysical data pertaining to the past distribution of substructural features of the volcanic complex of Vesuvius can only be deduced from the erupted products. The Vesuvian lithics consist of rocks surrounding the conduit region of the volcanic complex (lavas), metamorphosed (marble) and unmetamorphosed limestone rocks from the Mesozoic carbonate basement of the volcano, and magma chamber rocks (cumulates, rocks formed from reactions of magma with basement rocks). The Pompei deposits contain limestones, thermometamorphosed marble and skarn lithic ejecta, and large quantities of lava (Barberi et al., 1989), suggesting that the magma chamber and/or magma fragmentation levels were located between 3 and 5 km below the volcano. The 1631 deposits (see section 3.2.2) also contain large quantities of lava and rocks from magma chamber or magma fragmentation levels (Rosi et al., 1992). These data do not, however, fix well the

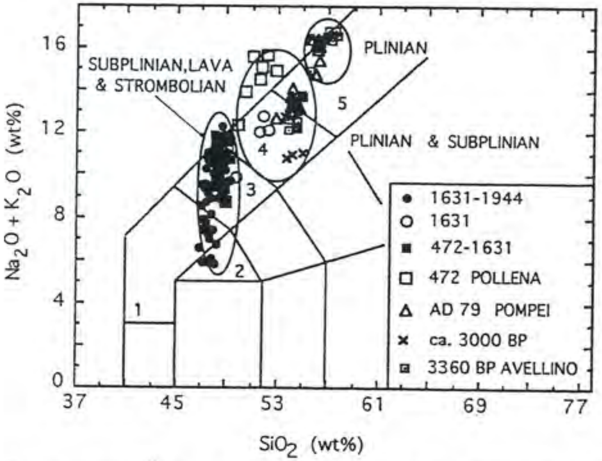

Figure 14. Magma compositions of plinian, subplinian, strombolian, and effusive eruptions of Vesuvius from 3400 BP to 1944 (Civetta and Santacroce, 1992).

magma chamber locations of plinian eruptions, and Barberi and Leoni (1980) hypothesized a depth between 2 and 3 km for the AD 79 eruption based on the equilibrium between products of eruption and thermometamorphic calcareous rocks.

Bouguer anomaly of the Vesuvian area (Cassano and La Torre, 1987) shows that the oriental sector of Monte Somma is characterized by a mass deficit or negative gravity anomaly, which may represent a collapsed or fractured zone of recent plinian eruptions. The positions of eruptive vents in the period 1890-1944 and opening of radial fractures (Fig. 13) *suggest* a cone-sheet structure of the superficial magma supply system of Vesuvius (Fig. 18). The existence of such a cone-sheet structure remains, however, to be verified in the future, whereas the depth of the basement of Vesuvius was established by the deep geothermal well Trecase (Balducci et al., 1985) drilled on the south slope of Vesuvius (Fig. 19) and by other geological studies (Principe et al., 1987). As further discussed in section 4.2, the geophysical studies at Vesuvius lag considerably the volcanological studies which also prevents the construction of a viable geological model.

2.3.3 Inferred Functioning of the Magmatic System of Vesuvius

Civetta and Santacroce (1992) state that "The advanced hypothesis is that Vesuvius, at least in the last 3,400 years, has to be considered, for what concerns magma supply, a sort of a steady-state volcano whose extremely variable eruptive behavior results simply by the different size of the magma reservoir, in its turn

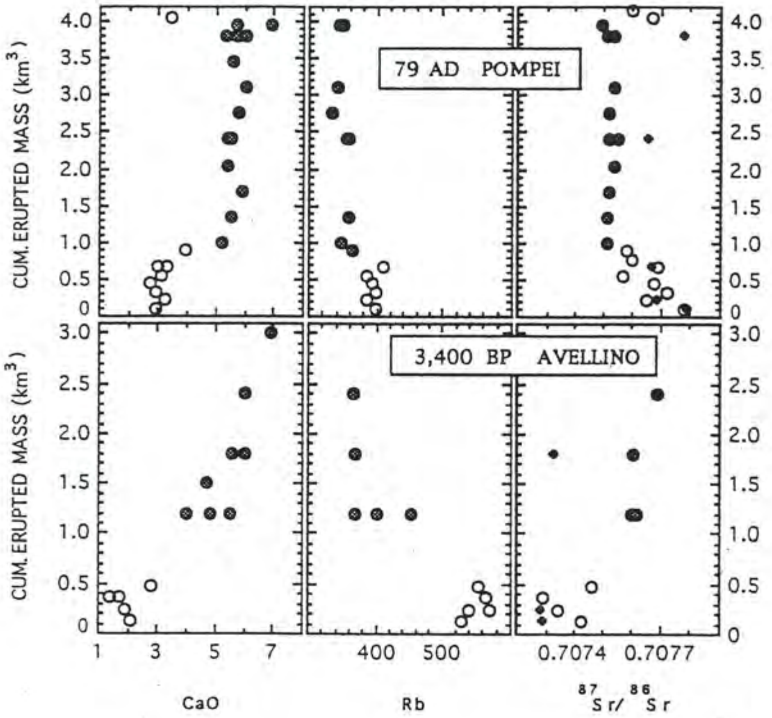

Figure 15. Chemical and Sr-isotopic variation of Pompei and Avellino plinian pumices. The cumulative erupted magma is expressed in dry-rock-equivalent. Open circles correspond to white pumice and closed circles to gray pumice. Diamonds correspond to separated K-feldspar at the same stratigraphic layer of the host pumice (Civetta and Santacroce, 1992).

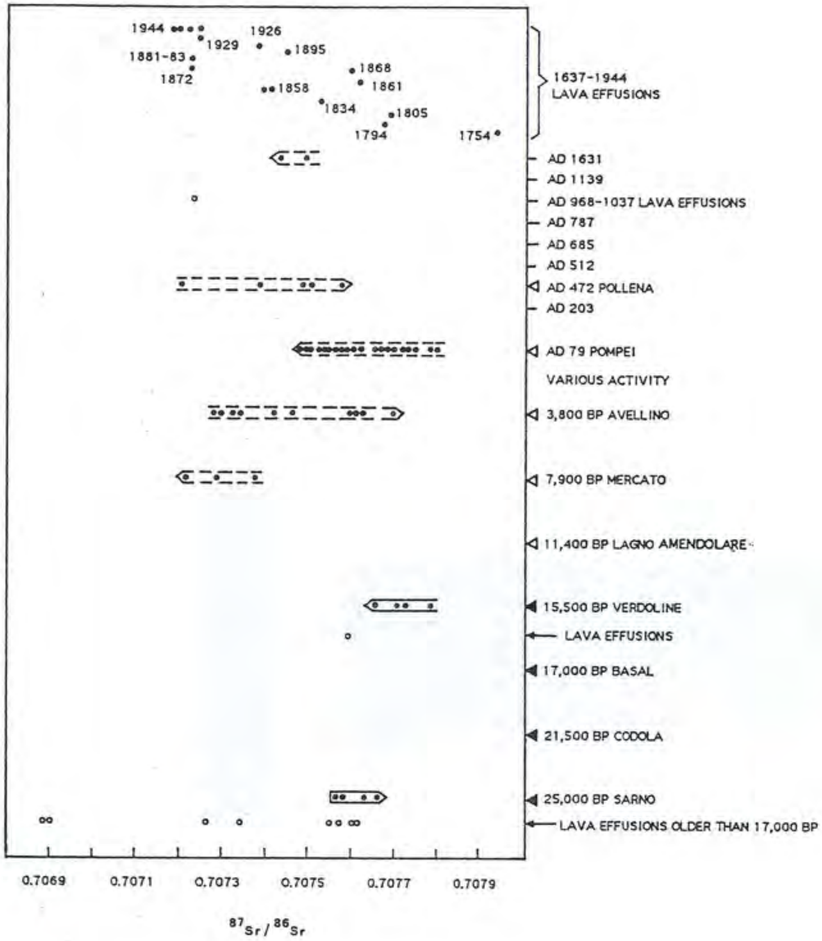

Figure 16. Sr-isotopic ratios of the Somma-Vesuvius volcanic products (compiled by Civetta and Santacroce, 1992).

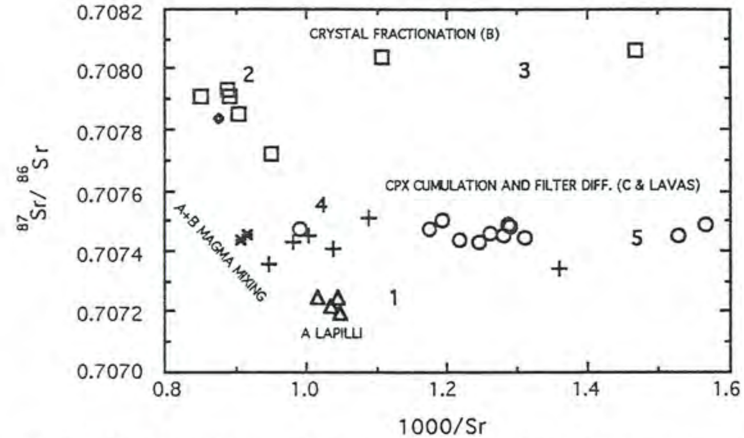

Figure 17. Sr-isotopic ratios of the 1906 eruption of Vesuvius. Triangles correspond to A lapilli, squares to B lapilli, circles to C lapilli, crosses to 1906 lava flows, and asterisks to 1895-1899 Colle Umberto cumulodome. The numbers 1,2,3 correspond to the eruption sequence (Civetta and Santacroce, 1992).

controlled by the depth of the obstruction of the conduit." In GNV (1992), two interpretations are given for the functioning of the magmatic system of Vesuvius: (1) continous magma supply, and (2) periodic magma supply. By considering 100-150 km^3 of volcanic products erupted from Vesuvius during the last 35,000 years of activity after the emplacement of the Campanian Ignimbrite, the *average* output rate is about 3-4$\times 10^6$ m^3/year (0.1-0.13 m^3/s). Between 1872 and 1906, Santacroce et al. (1992) calculated an average output rate of 3.5-4$\times 10^6$ m^3/year. Thus, by assuming: (1) that the magma supply rate after 1944 remained unchanged, and (2) that the eruption of 1944 totally emptied the Vesuvian shallow magmatic system (similarly to what is assumed to have occurred during the 1906 eruption), a volume of magma on the order of 1-2$\times 10^6$ m^3 should have entered into the Vesuvian system after 1944 (Santacroce, 1991). The volcanological and geochemical evidence, as discussed in section 2.3.1, suggests that each eruption of Vesuvius was produced by geochemically and isotopically different magma. In closed-conduit conditions with continous magma supply, this difference is associated with the magma withdrawal dynamics and magma chamber processes (crystallization, liquid fractionation), whereas in open-conduit conditions, it is associated with different magma batches which are fed from deep magma chamber(s) to shallower magma reservoir(s). In the case of the discontinous magma supply case, a rapid transfer of magma from the source to the surface is hypothesized to occur in batches or feeding units. The B magma body during the

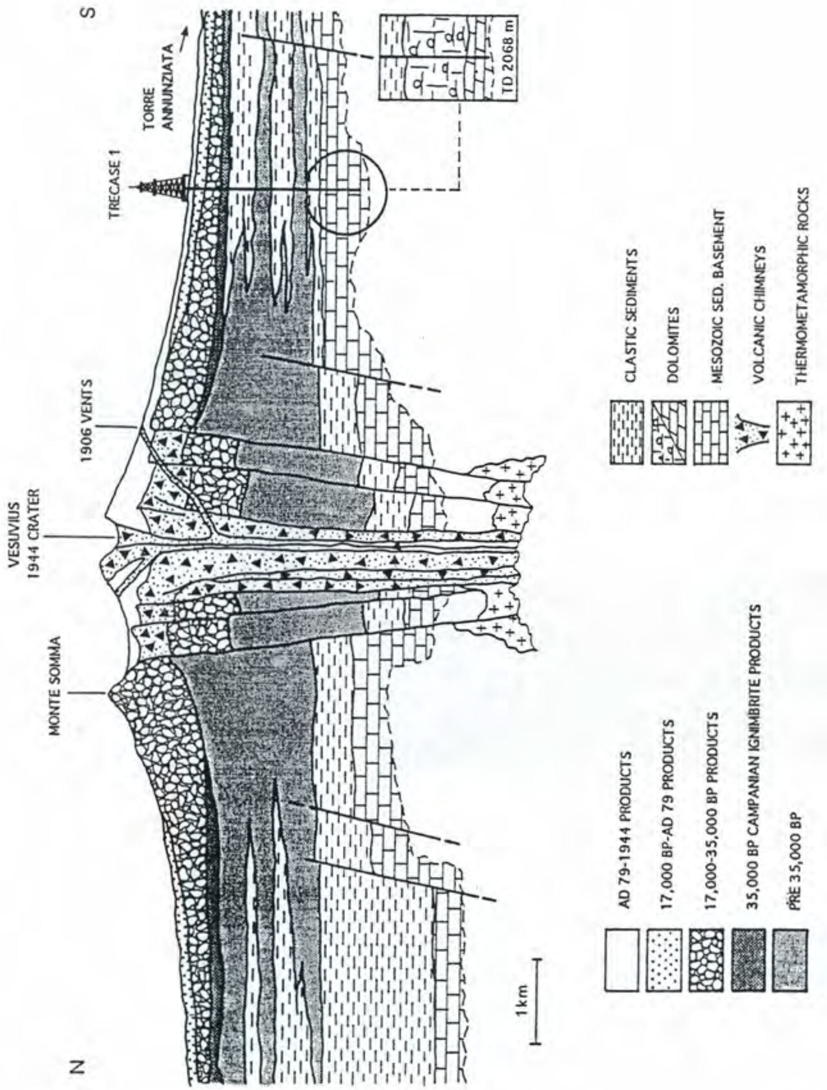

Figure 18. Inferred geological cross-section of the Somma-Vesuvius volcanic complex (Principe et al., 1987).

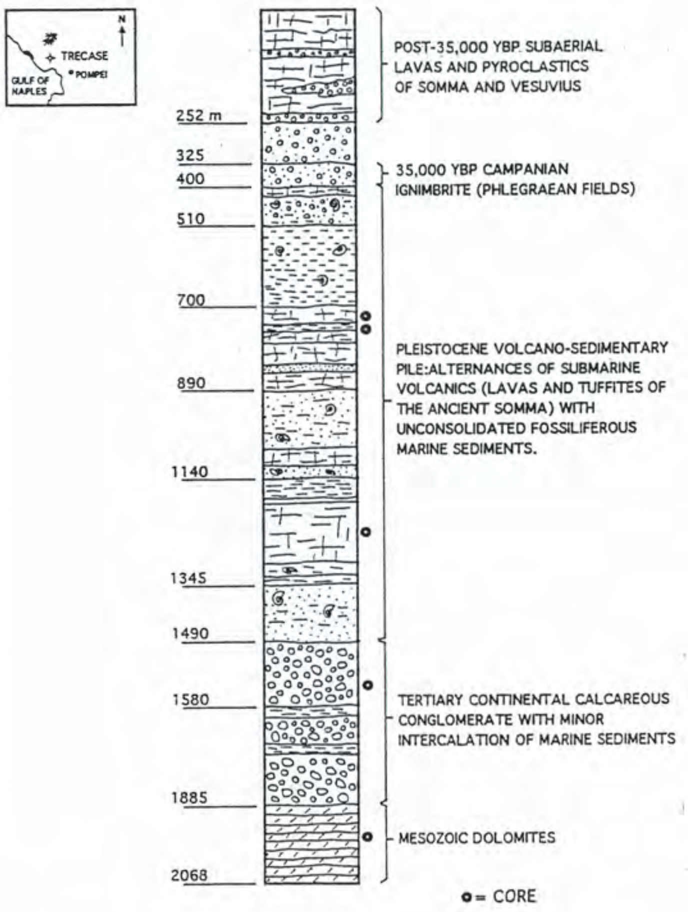

Figure 19. Stratigraphy of the Trecase geothermal well (Balducci et al., 1985).

1906 eruption was assumed as being one of these batches. It had a volume of about 6×10^6 m^3 and a mean density of 2600-2700 kg/m^3 (Santacroce, 1991), and, consequently, a mass of about 10^{10} kg. This body was compositionally and isotopically zoned. It was lighter and more differentiated in its upper portions and denser and richer in mafic crystals in its lower portions. Its Sr-isotopic ratio ranges from 0.7072-0.7080 which contrasts with the extreme values of the feeding units during the 1906 eruption (*i.e.* batches A and B shown in Fig. 17). According to Santacroce (1983, 1991) and Civetta and Santacroce (1992), the plumbing system of Vesuvius is characterized by periodic arrivals of small magma batches which form shallow revervoirs at or above the level of the boundary between the carbonate basement and the volcano-sedimentary cover. A possible feeding system of Vesuvius as hypothesized by Santacroce (1991) is illustrated in Fig. 20. Magma is produced from the melting of peridotite and is accumulated at the base of the crust, or Mohorovičić discontinuity (MOHO) located at about 20 km, and transported upward through the feeding zone into the upper and shallow magma reservoir(s). On its way through the feeding zone, magma may mix and fractionate and, depending on the open- or closed-conduit conditions, it may experience further differentiation in the upper zones of the volcanic complex.

Whether or not a continuous or discontinuous magma supply takes place into the Vesuvian system, in both closed- or open-conduit conditions, depends on the availability of magma at depth and on its driving pressure. Because the driving pressure is most likely the result of buoyancy, any factors that affect the density of magma could cause fluctuations in the flow-rate. A magma rising due to buoyancy when the conduit is closed will tend to become arrested and continue to spread laterally and melt the enclosing rocks in a region where the density difference between the rock and magma is reduced to zero. Since most rocks expand on melting (silicates about 10%), this will have a tendency to increase the local pressure, decrease the melting due to pressure increase, and induce rock fracturing. Upon fracturing of rocks, the melt pressure will decrease due to flow into the fractures which will produce more melting. A large-scale melting may, therefore, occur with considerable volume expansion and buoyant rise of magma to even higher levels of the system. This implies that the magma flux from deep regions should be dependent at least on the primary magma composition, abundance of magma within the deep and shallow regions of the volcano, and structural characteristics of the volcanic edifice. One should not, therefore, assume *a priori* either a continuous or episodic magma supply to the Vesuvian system. However, a periodic magma supply may be possible in the form of *diapirs* from fluid-dynamic considerations (Marsh, 1982; Spera, 1980; Whitehead and Helfrich, 1990).

Magma is formed by partial melting of mantle or crustal rocks followed by the segregation and separation from its refractory residue. When rocks partially melt, the liquid occupies spaces between grains of different minerals and, because

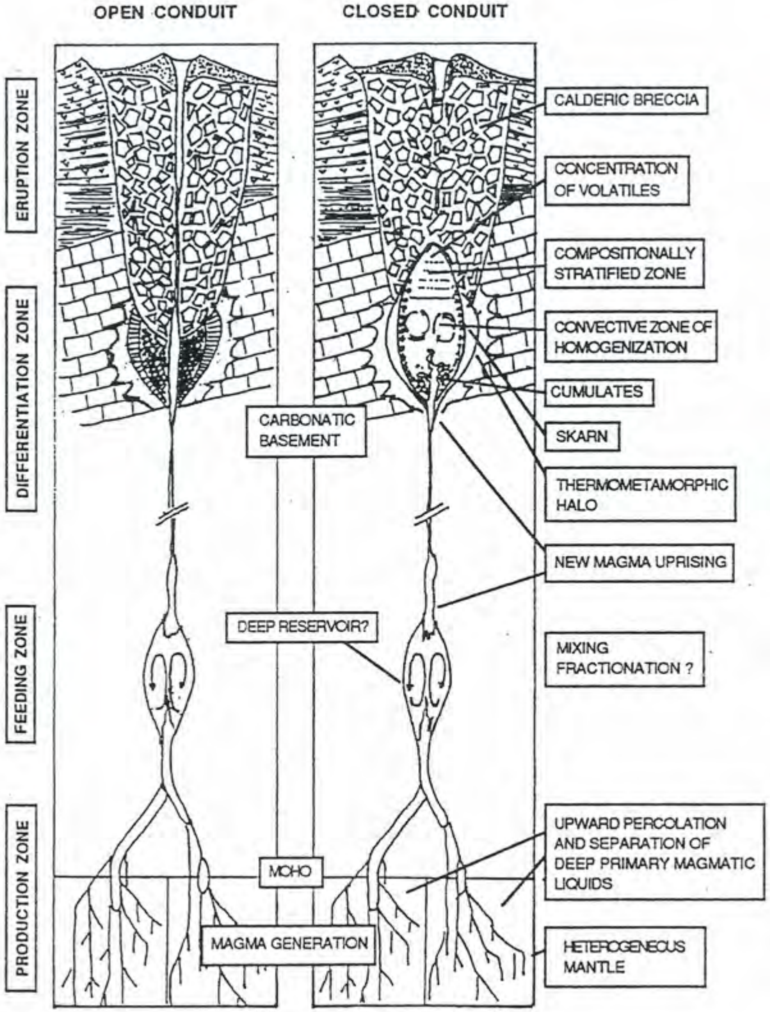

Figure 20. Schematic representation of a possible magmatic system of Vesuvius in open- and closed-conduit conditions (Santacroce, 1991).

of surface tension, the liquid spreads along grain edge intersections, and if the liquid fraction becomes significant, it can produce the necessary buoyant force for upward movement. Such a mass of liquid or diapir can then rise relatively fast compared to segregation time, and the magma supply to the Vesuvian system can be periodic with the frequency depending on the magma production zone of the volcano. Diapiric bodies of magma must remain, however, hot enough to be molten as they rise through the lithosphere. Many diapiric bodies passing through the lithosphere could, however, rise the rock temperature to such an extent that even relatively small magma bodies can be transported upward. Clearly, when considering the rise of magma diapirs from the magma production zone of Vesuvius, it is necessary to account in the model for the effects of heat transfer, fluid convection, and partial melting.

The complex refilling history of the Vesuvian magma chamber was also deduced by Civetta and Santacroce (1992) and Cortini and Hermes (1981) based on the isotopic and chemical variations of erupted pumices from plinian eruptions of Avellino and Pompei, and historical lava flows. The chemical zonations of the Avellino and Pompei deposits are interpreted as evidence of magmatic convection in the magma chambers (Turner, 1980; Hildreth, 1981), whereas the isotopic variation is related to the isotopic zoning in the chambers. It remains to be explained, however, why the Avellino and Pompei gray pumices have a fairly constant Sr-isotopic ratio whereas the white pumice displays a range of Sr-ratios. Sr-isotopic compositions showing a negative correlation with time along two different trends of lava flows at Vesuvius from 1754-1944 imply that the primary Vesuvian magmas are derived from two different (deep) magma reservoirs which became active contemporaneously from 1861-1881. Cortini and Hermes (1981) suggested that each of these trends is due to magma mixing in the two reservoirs. Since the end-members of the two trends do not differ in major element chemistry, this rules out bulk crustal contamination as a cause of the variation. The $^{87}Sr/^{86}Sr$ ratios have a great utility in igneous petrology, but they must be carefully examined to determine the effects of heterogeneity in the magmatic source regions, isotopic fractionation at the time of crystallization, contamination of magma, and subsequent hydrothermal alteration. The complex Sr-isotopic compositions of Vesuvian tephra and lavas stress the importance of *global* modeling of the volcanic complex where the physical, chemical, and isotopic characteristics of magma and rocks, thermofluid-dynamic processes of multiphase mixtures of magma, gas, and crystals, and the structural properties of the volcanic edifice play a crucial role in establishing the dynamics of different volcanic eruptions.

2.4 Definition of Reference Eruptions

The accurate characterization of physical, volcanological, petrological, and other characteristics of test cases or reference eruptions is essential for initiating a simulation and verification of a global volcanic simulator. The *initial conditions* of the simulator consist of the thermofluid-dynamic properties of magma, gas, and pyroclasts, and structural mechanics properties of the volcanic edifice involved in the simulation. These properties define the state of magma, gas, and rocks below and above a volcano, and must be defined accurately in the entire simulation domain or region of interest at the start of the simulation. These initial conditions, supplemented by the *boundary conditions* at the domain boundaries for all subsequent times, determine the evolution of the volcanic complex in time and space. If a simulation is initiated from a closed-conduit state of a volcano, then the simulation should be able to predict the subsequent volcanic eruptions. It is also important to note that the effects of the initial conditions on the evolution of the volcanic system tend to be forgotten in time, and that this is not true for the boundary conditions which in effect determine the system evolution in time and space. For these reasons, it is crucial to define correctly the simulation domain.

The Commission placed a heavy emphasis on a subplinian reference volcanic event typical of the 1631 eruption of Vesuvius. In view of its devastating nature, this eruption can be chosen as a reasonable first choice in an attempt to produce hazard-zonation maps for the Vesuvian area by means of a global volcanic simulator. As discussed in section 2.2, this eruption produced a plinian column, caldera collapse, pyroclastic flows and surges, and generated lahars and mud flows. A simulator should not only be able to simulate these effects accurately, but it should also *predict* the eruption or simulate its opening phases when magma begins to channel its way toward the surface. For this reason, the simulation should start prior to 1631 and the simulator should be able to simulate magma supply, differentiation, and crystallization in the magma chamber which lead to conduit opening and subsequent closure after the driving pressure for magma discharge is reduced and the eruption is terminated. To simulate these conditions, it is thus necessary to start the simulation with the initial conditions of Vesuvius which are known reasonably well.

The AD 79 Pompei eruption appears to be the best known event of Vesuvius prior to 1631. This eruption has been studied extensively and much is known about its magmatic system prior and after the eruption. The AD 79 eruption products have been extensively studied (for the more recent studies, see Civetta and Santacroce, 1992; Santacroce et al., 1993, in preparation) and it would be advantageous to test the simulator's predictions of magma chamber processes with the data of this eruption, before attempting to simulate the magma chamber processes of the 1631 eruption for which few data exist (Rosi et al., 1992). The drawback of this suggestion is, however, that the simulation would have to start *prior* to 79 AD and possibly around 700 BC when the conduit apparently closed after the Avellino event. By further going back in time, the Vesuvian events and data become more uncertain (Arnó et al., 1987) which produces difficulties in constraining the initial conditions. For these reasons, a global volcanic simulator for Vesuvius should begin simulation of its plumbing system *after* the AD 79 eruption, and continue the system simulation into the future.

The 1631 subplinian eruption did not, however, close the conduit of Vesuvius, and the simulator would have to predict this very important characteristic of the eruption. The predictions of the 1906 strombolian event and closure of conduit in 1944 are two additional characteristics of Vesuvian eruptions which a simulator should predict, if it can be considered useful for predicting volcanic eruptions. The simulation of volcanic events from 1631-1944 requires, therefore, that the simulator should be able to simulate the strombolian activities and effusive lava flows.

2.5 Concluding Remarks

Vesuvius has exhibited various types of activities for the past 35,000 years. Very large scale plinian eruptions occur from several centuries to millennia, subplinian eruptions one to several centuries, and strombolian and effusive activities every few decades. It appears that the strombolian and lava effusive activities follow the plinian and subplinian eruptions until the conduits close, and that the plinian and subplinian eruptions occur from the closed-conduit states of the volcano. From the petrological and volcanological evidence it appears that the volcanic activity at Vesuvius can be associated with a periodic magma supply to the Vesuvian feeding system. At present this result is, however, poorly constrained by thermodynamics, geophysics, and thermofluid-dynamics, since it ignores the state of the upper part of the volcanic complex in determining the evolution of its lower feeding part. A global volcanic simulator for Vesuvius will need to be constructed with interdisciplinary data for the purpose of supplying the initial and boundary conditions as well as for verifying the simulator with data from reference eruptions at Vesuvius.

3. Required Volcanological and Geological Studies Pertaining to Reference Eruptions

The development of a global volcanic simulator requires volcanological and geological data to define the volcanic system and verify the computer simulations. As discussed in section 2.4, the starting point of simulations may be initiated at the end of the Pompei eruption in AD 79 or immediately thereafter when the volcanic conduit closed. For a crucial test case of the simulator, it was suggested to employ the 1631 eruption. The subplinian eruption of Vesuvius in 1631 produced a plinian column, caldera collapse, pyroclastic flows and surges, and lahar and mud flows which can be used to verify physical models of magma chamber convection and crystallization, magma ascent along the conduit, structural-mechanics behavior of the volcanic edifice, volcanic column, pyroclastic flows, and lahars. The required volcanological and geological studies discussed in this section pertain to three general categories: (1) studies aimed at identifying the initial conditions of the Vesuvian volcanic complex after the AD 79 eruption, (2) studies aimed at characterizing the 1631 eruption, and (3) general studies of Vesuvius.

3.1 Definition of Initial and Boundary Conditions

The reduction of the uncertainty in initial conditions data and computer simulation time can be accomplished by initiating the simulation after the termination of the eruption in AD 79 or thereafter when the conduit closed. Starting from a closed-conduit condition eliminates the need to specify the conditions of magma flow in the conduit and of the volcanic column above the vent which are difficult to assess. For these reasons, it is suggested to study the events at Vesuvius following August 25, AD 79 and determine the conditions of the Vesuvian volcanic complex at the time of conduit closure.

3.1.1 Establishment of Conduit Closure Date After AD 79 Eruption

The lack of scientific insight of the historians and chronicles after Pliny the Younger who described the eruption of Vesuvius in AD 79 is reflected in the absence of reliable data in the centuries following this eruption (Arnó et al., 1987; Alfano, 1924). As reported by Alfano and Friedlaender (1929), the first eruption of Vesuvius after AD 79 occurred in AD 203, and between AD 203 and AD 205 moderate activity at the central crater seems certain (Arnó et al., 1987). After AD 205, no eruptions appear to have been recorded until the Pollena subplinian eruption in AD 472. A thorough search of old documents and volcanological studies of deposits are required to ascertain when the conduit closed after August 25, AD 79. From these studies, it would be of great importance to ascertain any strombolian and lava flow activities which preceded the conduit closure, as occurred after the eruption of 1631. Moreover, it would be valuable to establish whether or not these types of activities *always* followed the plinian and subplinian eruptions of Vesuvius.

3.1.2 Definition of Substructural Conditions

The substructural conditions at Vesuvius can be conveniently divided into magma supply conditions, magma differentiation conditions, and volcanic edifice conditions. The magma supply conditions refer to the magma and rock properties below the magma chamber. In this region, magma is transported toward the surface of the Earth through a geothermal gradient where it may undergo differentiation, contamination, H_2O and CO_2 variations, *etc.* Magma differentiation conditions pertain to the properties of magma chamber where magma mixing, crystallization, assimilation, and exsolution may take place. The volcanic edifice conditions pertain to the properties which define the volcanic edifice and includes the thermal and mechanical states of rocks surrounding a magma chamber.

Magma Supply Conditions

The establishment of flow, thermodynamic, and rheological properties of magma entering a magma chamber is crucial for modeling of magma chamber processes as discussed below in section 6. To properly establish these properties it is necessary to employ petrological, geophysical, and thermofluid-dynamic constraints pertaining to mineralogy and melt transport from the mantle to the upper crust underneath a magma chamber. The following research objectives should be pursued:

1. Geophysical studies to ascertain the seismic P- and S-wave velocities in the Vesuvian area as accurately as possible in order to establish the possible mineralogy of the source giving rise to the primary Vesuvian magma.
2. Since the mantle is considered nonhomogeneous (Wyllie, 1988), studies are needed to establish not only the main but also the accessory minerals and the effects of presence or absence of H_2O and CO_2 in the upper mantle on the magma genesis and differentiation below the magma chamber of Vesuvius. Some important steps in this direction have already been taken by Dolfi et al. (1987) and Trigila (1990). The determination of *thermodynamic phase diagrams* of rocks in the magma production zone of Vesuvius and establishment of *geothermal gradient(s)* in this region are essential for constraining magma transport.
3. The thermofluid-dynamic constraints of magma transport in the supply region of Vesuvius have not been employed satisfactorily to date to explain the functioning of this region. When this is accomplished, it may provide some surprises regarding the hypotheses discussed in section 2.3.3. The buoyancy force on magma is determined by the magma composition, geothermal gradient, and thermodynamic and stress characteristics of local rocks. These characteristics determine magma density, viscosity, crystal content, and melt fraction which establish the capacity of magma to channel its way through the porous rock matrix. Thermofluid-dynamic studies are, therefore, required to *constrain* the flow of magma from the production zone below the volcano. These studies may constrain magma transport by diapirs or through time-evolving fractures produced by the magma itself. Section 6.2.1 discusses in more detail the required thermofluid-dynamic modeling research pertaining to melt segregation and transport in the presence of a geothermal gradient.

4. Magma assimilation depends on the primitivity of magma, with more primitive and, therefore, less viscous and hotter magma being able to assimilate more effectively than colder and more evolved and viscous magma. This assimilation may change the Sr-isotopic ratios of erupted magmas and may explain some of the observed radiogenic variations as discussed in section 2.3.1. Fundamental petrological studies are needed to increase our knowledge of the primary Vesuvian magma(s).
5. Experimental petrology is a very powerful tool to investigate the processes of production and differentiation of magma in the Vesuvian area. However, much more work is needed in this direction which should lead to a general model capable of explaining the existence of three different periods in the history of Vesuvius: the first one from 25,000-15,000 BP characterized by slightly undersaturated magmas, the second one from 7,900-1,850 BP characterized by phonolitic-tephrites to phonolite, and the third one from 1850 BP to the present characterized by leucitic-tephrites to phonolitic-leucitites.
6. Almost the totality of geochemical and isotopic studies before the 1631 eruption are concentrated on the products of the plinian or subplinian eruptions (Avellino, Pompei, Pollena). To produce a general model of the behavior of Vesuvius also requires the determination of the products and the types of activities during long active periods between the plinian events. This implies that an exhaustive geochemical study of the volcano at present must be accompanied by a parallel volcanological investigation aimed at the reconstruction of the minor events between the plinian eruptions, with an extensive use of the method of radiocarbon dating.
7. A large number of Sr-isotopic determinations has been made on the Vesuvian products, whereas much less information has been produced with other isotopes. Recent work indicates, however, that the simultaneous determination of several isotopic ratios (namely, $^{143}Nd/^{144}Nd$, $^{87}Sr/^{86}Sr$, $^{18}O/^{16}O$, and isotopes of the U-Th decay series) is a powerful tool for investigating the geological processes connected with the generation, differentiation, mixing, *etc.*, of magmas (Faure, 1986). At present, Nd-isotopic ratios have been measured only for the Avellino, Pompei, and Pollena eruption products (Civetta et al., 1987, 1991), and Th, U, and Ra-isotopic distributions have been determined for the products of the 1944 eruption (Capaldi et al., 1982).
8. No significant attempt has been made by researchers to quantify the important processes they detected on geochemical and isotopic bases. For example,

many authors agree on the existence of mixing between magmas with different isotopic ratios in the period from 1754-1944 (Cortini and Hermes, 1981; Cortini and Scandone, 1982, Civetta and Santacroce, 1992), but no application of the theory of isotope ratios in two component mixtures (Faure, 1986) has been made to date.

Magma Differentiation Conditions

The plinian and subplinian deposits of Vesuvius contain lithics which came from deep regions of the volcano where the magma chambers are assumed to exist (Barberi et al., 1981; Santacroce, ed., 1987). Physical modeling of magma chamber requires the definition of its size, initial fluid (in general, liquid, gas and crystals) conditions in the chamber, and stress, thermal and fluid-dynamic conditions at its boundaries for the entire duration of simulation. At present, little is known about any of these conditions for Vesuvian magma chambers and a considerable effort should be invested in increasing our knowledge of them.

Magma chambers can exist if the melt fraction is sufficiently large and may move depending on the melt buoyancy. The plinian and subplinian magma chambers of Vesuvius may have had sizes ranging from 0.1-50 km^3, and possibly larger. They may have formed by diapirism, stopping, and flow in dykes, or by a combination of these mechanisms. For example, small diapirs may contribute to the creation of a large chamber preceding a plinian eruption. After the eruption, the roof of the chamber collapses (inferred from the observations of caldera formation) whereby the xenoliths or rocks from conduit and magma chamber walls break off and may settle to the bottom. This may then lead to the upward movement of a magma chamber and be responsible for strombolian eruptions and changing magma compositions (by the assimilation of conduit and magma chamber wall rocks with magma) in the chamber following the plinian event. As discussed in section 2.3.1, the subplinian deposits at Vesuvius lack carbonate lithic ejecta; it should be established if this implies that the magma chambers moved to shallower regions of the volcano after the plinian events.

Knowing the location, geometry, size, and composition of melt and solids in the magma chamber following the conduit closure after AD 79 is indispensable for modeling the subsequent evolution of the chamber. These and other data are poorly constrained at present and a significant effort should be directed toward understanding of:

1. Lithics in AD 79 deposits to establish their *origin during eruption.* The results of this study may help to *constrain the magma chamber location and movement through time* as the eruption was terminating.

2. Tephra deposits to ascertain time-wise distribution of magma composition and its assimilation with chamber wall rocks. It is necessary to establish the composition of magma (including volatiles), crystals, and the nature of the country rocks at the time of conduit closure in the magma chamber. To accomplish this objective, it is also necessary to initiate appropriate experimental studies. The results of these investigations should be presented in terms of thermodynamic phase diagrams and tables for wide ranges of magma chamber temperatures and pressures. The uncertainties in magma composition should be expressed with several phase diagrams which *constrain the range of possible compositions.*

3. Tephra deposits to establish liquid, solids, and gas fractions in the magma chamber following the conduit closure. These fractions and liquid, solid, and gas masses in the chamber are employed as initial conditions in physical modeling equations and need to be established.

4. Crystallization and crystallization kinetics. The composition of a multicomponent liquid is changed dramatically by the crystallization of a mineral phase, especially when the composition of the mineral differs significantly from that of the liquid. Crystallization is limited by the rate at which new crystals nucleate and grow. As the pressure, temperature, and composition of magma change, the equilibrium melt-crystal assemblage will also change, and the latter may lag behind its equilibrium composition. These effects need to be studied to determine the effects of crystallization and crystal kinetics parameters on composition for the magma following the AD 79 eruption of Vesuvius.

5. Magma and crystal rheology. For the range of the above compositions, magma density, viscosity, and chemical and thermal diffusivities of liquid components also need to be established, with possible effects due to kinetics. The rheological parameters and crystal content of magma can significantly affect magma chamber convection (see section 6) and the initiation and subsequent evolution of volcanic eruption. For these reasons, the determination of these parameters is critical for accurate modeling of magma differentiation and crystal fractionation in a magma chamber.

6. Vapor phase differentiation. The convection in a magma chamber can separate differentiated liquids and cause release of volatiles, which in turn produces further differentiation. A magma chamber can also exchange volatile species with the surrounding rocks following a volcanic eruption when water from fractured walls pours into the chamber. Studies pertaining to volatile release and water incorporation into magma spanning the compositional range and magma chamber state(s) after the conduit closure following the Pompei eruption are necessary for properly defining models of magma chamber processes.

Volcanic Edifice Conditions

Volcanic edifice conditions involve the properties which define the thermal and mechanical states of rocks surrounding a magma chamber. Magma and crystals in a magma chamber continuously exchange heat with the surrounding rocks and vary their stresses, as the magma is supplied into the chamber under closed-conduit conditions. These heat and stress effects can induce metamorphism of the rocks surrounding the chamber and change in time their mechanical and thermal properties. On time scales involving long repose times between plinian eruptions of Vesuvius, the rocks in the immediate surrounding of a magma chamber, where pressures and temperatures are high, can become ductile and may behave more like a very high viscosity fluid rather than behaving as elastic solids. This is especially true if water is present in the immediate location of a magma chamber, since water weakens the chemical bonds in minerals. Limestone and marble, which form the basement of Vesuvius, can readily deform by ductile deformation in the presence of water and under high pressure and temperature conditions, thus contributing to the effective formations of plinian magma chambers. Numerous volcanic events at Vesuvius since the AD 79 eruption have changed the structural characteristics of the volcanic edifice to such an extent that it may not be reasonable to expect today that these characteristics are similar to those of nearly 2000 years ago. The required geological and geophysical research to understand the *present* volcanic complex of Vesuvius is described in section 4. The required studies pertaining to the definition of volcanic edifice conditions include:

1. Establishment of the geometrical shape of the cone of Vesuvius following the AD 79 eruption and definition of stratigraphy. The only deep stratigraphy of Vesuvius known at present is that from a geothermal well drilled near the village of Trecase (Balducci et al., 1985) on the SE slopes of the volcano. The drilling started at 220 m above sea level and stopped at a depth of 2068 m (Fig. 19). In the absence of other well data and since there is no reason to expect further drillings in the foreseeable future, it is necessary: (1) to establish whether this stratigraphy is representative at other sites of the volcano and, in particular, along the central portion below the caldera, and (2) whether this stratigraphy can be used for the Vesuvian area following the conduit closure after the AD 79.
2. Tectonic studies aimed at identifying different geometrical parts of the volcanic edifice. These studies would also have to address the stress distributions in various parts of the volcano following the conduit closure after AD 79. In particular, it is required to identify the state of stress of rocks at magma chamber depths and structures and conditions which can cause failure. Recent works of Zoback (1992) and Müller et al. (1992) may be useful in estimating the regional tectonic stress.

3. Establishment of a *geologic model* of Vesuvius. This work pertains to the definition of subsurface parts of the volcano, such as the radial, lateral and cone structures, dykes or eruptive fissures, and the extents and densities, porosities and permeabilities of each of the nonhomogeneous parts of the Vesuvian system up to and beyond the magma chamber depth. These geologic data must be properly constrained by petrology, geothermobarometry, seismology, and geophysics (see section 4.2). The subsurface Vesuvian complex should also be identified with different temperature regions and physical properties of rocks established as a function of temperature. The establishment of the degree of saturation of rocks in different regions of the volcano is also of paramount importance. This information is needed to produce *deformation maps* as discussed in section 6.3.

The definition of volcanic edifice conditions at the time of conduit closure after the AD 79 eruption is clearly problematic. Nevertheless, a serious attempt should be made to achieve this goal. The present geological model of Vesuvius may serve for such a purpose, but, unfortunately, not enough effort was dedicated in the past to produce such a model. Section 4 of the report deals with the discussion of the geophysical studies at Vesuvius which are required for the understanding of the Vesuvian subsurface geological structures.

3.2 Identification of 1631 Eruption Parameters

The 1631 subplinian eruption of Vesuvius can be characterized by: (1) an initial phase during which a fracture opened in the WSW sector, from the top of the cone of Vesuvius to its base on the plain of the Somma caldera, with emission of gas and ejection of incandescent blocks and scoriae; (2) a plinian phase which lasted from 8-10 hours; (3) an eruptive phase characterized by a succession of seismic shocks with associated ash showers and extensive rainfall; (4) a pyroclastic flow phase; and (5) a phreatomagmatic phase. The products of the eruption formed a wide variety of pyroclastic deposits, from plinian fallout to dry pyroclastic flow and surge deposits, and fine-grained ash and lahars (Rosi et al., 1992). As discussed in section 2.4, the eruption of Vesuvius in 1631 represents a good test case for verifying the simulator predictions, and the Commission chose this eruption as a reference event for the construction of hazard-zonation maps for Vesuvius. The eruption of 1631 has been described by many contemporary chronicles which have been recently examined by Rosi et al. (1992) in order to determine its dynamics. The volcanological and geological studies required to construct a simulator can be divided into three broad categories: (1) historical studies, (2) stratigraphic studies of deposits, and (3) magma composition and crystal distribution studies.

3.2.1 Historical Studies

Rosi et al. (1992) have examined about 200 historical accounts of the 1631 eruption of Vesuvius (bibliography given in Riccio, 1889), with preference given to authors who eyewitnessed the eruption. A close scrutiny of these accounts is important for establishing the pre- and post-eruption geometry of the cone, location of eruptive vents and their motion in time, progression of eruption styles, and for quantifying some of the eruption parameters. Many of these accounts should be re-examined in light of the modeling requirements which demand *quantification* of eruption parameters. These include:

1. Reconstruction of the geometrical shape of the cone of Vesuvius and its changing characteristics during the eruption.
2. Identification of vent geometries during the eruption, locations of fractures and vents and their motion with time, and correlation with different eruption styles.
3. Determination of column parameters, such as column heights, widths, and types (plinian, partial collapsing, fully collapsed) and their variation with time.
4. Identification of rain parameters, *i.e.*, whether the rain came from eruption clouds and/or from magma interacting with water from aquifers, and at what stages during the eruption.
5. Determination of pyroclastic flow, lahar, and mud flow parameters, such as distribution of flow branches, direction of motion, relative size, velocities, temperatures, and correlation with surroundings (houses, people). These observations may suggest whether the flows were dense, dilute, hot, mobile, destructive, *etc.*
6. Causes of death which can give indications of different phenomena in different parts surrounding the volcano.

3.2.2 Stratigraphic Studies of Deposits

Arnó et al. (1987), Barberi et al. (1989), Rolandi and Russo (1989), and Rosi et al. (1992) carried out stratigraphic studies of the 1631 deposits. The latter authors identified six stratigraphic units whose properties are important to summarize in order to define further volcanological research required for testing of physical models of volcanic processes as discussed in section 6.

Unit I or *basal, crystal-rich sand fallout* deposit consists of reversely-graded volcanic sand with a maximum thickness of 13 cm at 1.8 km from the vent along the dispersal axis. In the same section, the deposit contains high amounts of lithic

lavas (about 30 wt%) and the highest quantity of loose crystals of the whole 1631 sequence (about 25 wt%). The deposit thins out very quickly away from the vent to less than 4 cm at about 3 km from the crater.

Unit II is the *main plinian fallout* deposit, and its isopachs, showing an eastward dispersion, are illustrated in Fig. 11a. The maximum observed thickness is about 1 m at 1.8 km from the vent, whereas in the distal section at about 31 km, near the dispersal axis, the deposit is 8 cm thick. The fallout layer is characterized by a sharp change in color in its middle portion, from greenish-gray below to dark greenish-gray above. Bulk chemical analyses of juvenile clasts, granulometric studies, and field observations (Rosi et al., 1992) show that this transition is accompanied by a more mafic character of the upper portion and by a frequent reverse grading. Juvenile clasts contain cm-sized crystals of leucite, biotite, and sanidine in a partly glassy groundmass with mm-sized crystals of clinopyroxene, plagioclase, and Fe-Ti oxides. The present scarse number of available granulometric and component analyses (6 natural sections were analyzed by Rosi et al., 1992) does not allow a complete characterization of the deposit. Lithics in these sections are characterized by fresh and altered lavas and tuffs, subrounded by quenched cumulates bearing interstitial glass, metasomatic rocks (skarns), felsic subvolcanics, and rare marbles.

Unit III or *fallout of blocks and ash* and Unit IV or *upper-lithic-rich fallout* show limited areal distribution. At the only section where they were observed (1.8 km east from the Vesuvian crater), Units III and IV show large lithic contents (Unit III 47 wt%, Unit IV 78 wt%) with a large proportion of cumulates and metasomatic rocks (Unit III 32 wt%, Unit IV 31 wt%). In the same section, free crystals amount to 16 wt% and only 3 wt% in Unit IV.

Unit V or the *ash flow/surge deposits* are unconsolidated, generally massive deposits which fill paleovalleys around the Somma Vesuvius complex, except in the north and north-east sectors which are shielded by the Monte Somma topographic high. Near the crater the deposits show at the base a discontinuous 2-3 cm thick ground layer depleted in fine ash (layer 1 of Sparks, 1976). In the distal zones (about 7 km from the crater) the lowermost 10 cm are finer and reversely graded, and show dune-bedding (layer 2a of Sparks, 1976), and grade up into the massive and coarser part of the ash flow (layer 2b of Sparks, 1976). The nonabundant grain size analyses indicate that deposits are rich in fines, with a proportion of ash less than 2 mm from 54-90 wt%, and less than 63 μm from 7-15 wt%. Lithics abound from 54-69 wt% and are mainly constituted of lavas (55-70 wt% of the total), whereas the free crystal content is moderate (11-18 wt%). In some natural sections on topographic highs, the pyroclastic surge deposits occur in the same stratigraphic position of the ash flow deposit.

Unit VI is composed of *fine-grained phreatomagmatic ashes* (Fig. 11c) which show an overall fallout origin and are composed of very fine material (at 1.8

km from the crater the proportion of ash less than 2 mm in size is 93 wt%). These ashes are made up of plane parallel, centimetric beds of vesiculated tuffs, accretionary lapilli and structureless ash, but the overall primary thickness is hard to assess due to erosion and incorporation in the soil.

The lahar deposits indicate that some of them were formed in the course of the eruption, whereas others were generated by remobilization of tephra after the eruption.

The above summary of deposits indicates complex eruption dynamics and lack of important information required for physical modeling of columns, pyroclastic flows, surges, and lahars. For this purpose, a *modeling-oriented stratigraphic study* of deposits is required. In particular:

1. Topographic reconstruction of Vesuvius and its surroundings prior to the eruption of 1631. It is necessary to establish this topography in order to verify the physical models of columns, pyroclastic flows, and lahars (section 6). At present, a 1:25,000 scale map of the Vesuvian area is available from Istituto Geografico Militare located in Firenze, either on paper or magnetic tape which can be used to establish the topography of Vesuvius following the AD 79 eruption. For studies of lahars and pyroclastic and lava flows, a scale map of 1:5,000 is highly desirable which the Regione Campania produced from 1975-1980. It remains to be established, however, whether this map is available in digitized form as required for computer simulations. Once digitized, the map must be corrected for the eruption products emplaced during and after the 1631 eruption and for topographic changes produced by men. The reconstruction of the topography prior to the 1631 eruption of Vesuvius may also require the use of appropriate geophysical studies (gravimetric, electric resistivity, *etc.*), as discussed in section 4.2.
2. Detailed study of each stratigraphic layer to establish the composition and density of erupted material (pumice, crystals, lithics), particle size spectrum, and volumetric or mass fractions of different particle or clast sizes.
3. Distribution studies of deposits. A sufficient number of stratigraphic locations must be selected to produce a *complete stratigraphic correlation* of the deposits of the 1631 eruption. In particular, it is necessary to establish the time-wise deposition of material in deposits and correlation between different locations.
4. A detailed study of the *provenance and characteristics of lithics* during the eruption is indispensable for the understanding of magma chamber and conduit wall characteristics. A magma pressure drop along a conduit (Dobran, 1992a) can produce inward and outward wall collapses, leading to erosion (Macedonio et al., 1992) and magma-water interaction (Dobran, 1992a; Dobran and Papale, 1992a) along a volcanic conduit. The lithics should also be scrutinized for metamorphic changes produced by pressure, temperature, and differential stress, and the lithic studies should be correlated with the stratigraphy of conduit and its surroundings.
5. A thorough study of crystal morphology is required to establish conditions (undercooling, concentration gradients, growth rate) at which they were formed. This pertains to crystals grown in the magma chamber and along the conduit.
6. Most, if not all, eruptions of Vesuvius demonstrate magma-water interactions (Santacroce, ed., 1987). Water appears to be available at various levels, with the aquifers being activated depending on the eruption style. It is important to identify from the products of the 1631 eruption the *location and thermal states* of aquifers. It is also important to identify the aquifer characteristics (geometry, porosity, permeability) and the metasomatic effects produced in rocks due to the circulating fluids (water, brine) in contact with high temperature environments.
7. Reconstruction of the time-wise behavior of mass flow-rates during the plinian and pyroclastic flow phases of the eruption are also necessary, where the effects of wind in this reconstruction must be properly evaluated (Bursik et al., 1992, Sparks et al., 1992; Papale and Rosi, 1993).
8. A thorough study of the relationship between the erupted material and missing cone volume of Vesuvius after the 1631 eruption is required. Rosi et al. (1992) already performed some initial calculations to establish this relationship.

3.2.3 Magma Composition and Crystal Distribution Studies

The composition and crystal content of magma can dramatically affect the eruption dynamics (Dobran et al., 1992; Papale and Dobran, 1992a, 1992b). For this reason, magma studies should be undertaken to establish its properties *during the entire course* of the 1631 eruption of Vesuvius. Specifically:

1. The composition of a liquid magma can be studied by: (a) microprobe analyses of glass inclusions contained near the border of phenocrysts which were equilibrated with the residual liquid immediately preceding different eruption phases, and which did not subsequently react with the host mineral; (b) XRF analyses of the mechanically-separated glass and microphenocristic portion of juvenile products; and (c) subtraction of the mineralogic composition by the bulk composition. Method (a) is also able to provide the dissolved water content in the magma just prior to the eruption.

2. Knowledge of crystal distribution in magma during the entire eruption duration is fundamental for establishing the density and viscosity of the mixture of liquid and crystals. The available results of crystal distribution studies on the two compositional types erupted during the plinian phase and on few samples of pumices from the pyroclastic flows of the 1631 eruption (Rosi et al., 1992), are not sufficient and should be integrated with a larger number of analyses.

3. A better characterization of magma during the phreatomagmatic phase is needed. This characterization may be difficult due to the fine fragmentation of the magma during explosive magma-water interactions.

4. The pressure and temperature conditions of magma before eruption can be investigated by studying equilibrium relations between: (a) the crystals and the residual liquid from which they were formed, (b) two or more crystal species in chemical equilibrium, and (c) two or more end-member constituents of a given mineralogical species in a single crystal. For further details of using the method (c), the reader is referred to section 5 which describes the required thermodynamic parametrization studies of magma. An interesting way to obtain physical parameters in a magma chamber consists in using the appropriate samples of the erupted magma in a series of "experimental runs" in which the samples are heated above the liquidus temperature and then cooled at various conditions of pressure, oxygen fugacity, and dissolved water content until reproducing the initial mineralogical assemblage. Such a procedure is also capable to provide clues on magma chamber processes such as mixing, chamber wall rock assimilation, and repeated cooling and heating episodes. The determination of *thermodynamic phase diagrams* of the liquid-gas-solid compositions spanning the appropriate pressure and temperature ranges of erupting magma is crucial for the development of a volcanic simulator (see section 5 for further details).

5. The establishment of crystal kinetic parameters (nucleation and growth rates) of *all crystallizing phases* in the magma chamber is essential for the proper modeling of magma chamber processes (differentiation, volatile exsolution, mixing, cooling at margins, *etc.*). Crystal growth is a complex process involving numerous steps, each of which proceeds at its own rate, with the slowest one determining the overall growth rate of the crystal. Different minerals growing together may have different rate-controlling steps, as may different faces on a single crystal. The gradients of temperature, pressure, composition, and stress affect these rates, and the texture of the crystallizing phase is a complicated record of these different rate processes. Crystal kinetic studies are very difficult and should be undertaken very seriously in order to make a modeling progress of magma chamber convection and crystallization.

6. The Sr-isotopic ratio determinations of the 1631 erupted magmas is important for the establishment of magma chamber processes and magma provenance. As discussed in section 2.3.1, the Vesuvian magmas exhibit a range in the Sr-isotopic ratios which have not been adequately explained to date. The few available data (Fig. 16) of the 1631 eruption are not sufficient and a much more thorough study is required to ascertain the limits of the Sr-isotopic variations.

7. Magma kinetics effects. The withdrawal time of magma during an eruption may affect the exsolution of gas dissolved in magma. This may be especially important during the initial transient periods of the eruption where the withdrawal times may be few seconds (Ramos and Dobran, 1993). For this reason, the equilibrium exsolution assumption may be in error and significantly less gas may be exsolved from magma during its transit from a magma chamber to the surface of the Earth. Thermodynamic studies of magma exsolution are therefore required to establish the *rate of exsolution* of Vesuvian magmas as a function of pressure and temperature. Some of these studies are described below in section 5.

3.3 General Studies of Vesuvius Including Lava Flows

3.3.1 General Studies of Vesuvius

The general geological and petrological studies of Vesuvius should be aimed at understanding the long term functioning of the volcano. This understanding can provide useful clues on the magma feeding system, magma differentiation region, and subsurface structural characteristics.

Santacroce (1992) presented to GNV a five-year geological and petrological research program for Vesuvius aimed at: (1) producing a new 1:5,000 scale geologic map of the Vesuvian area, (2) studying distal deposits of plinian and subplinian eruptions, (3) establishing eruptive and depositional mechanisms of pyroclastic flows from eruptions younger than 17,000 years, (4) determining the chemical and physical characteristics of erupted products, (5) studying the pyroclastic sequences in order to understand magma-water interactions, (6) determining magma evolution in the magma chamber, and (7) understanding of primitive magmas and feeding system of Vesuvius at depth. The proposed program was not aimed at developing a simulator, but its objectives complement the volcanological and geological studies required for the identification of reference eruptions as discussed above for the purpose of constructing a global volcanic simulator of Vesuvius. The geological and petrological research program of Santacroce is much more ambitious than that required to develop the simulator, if implemented with significantly larger resources than requested by him. Nevertheless, we will summarize the proposed studies below and indicate more precisely where they are complementary.

1. The development of a 1:5,000 geologic map of Vesuvius is consistent with the requirements of simulator for reconstructing the Vesuvian topography before the 1631 eruption (section 3.2.2).

2. Studies of distal deposits are important for establishing the behavior of large-scale plinian eruptions and ascertaining episodic behavior of magma feeding. This work complements the required research in section 3.1.2 aimed at the definition of magma supply conditions at Vesuvius, and section 6 aimed at developing physical models of volcanic columns.

3. The studies of eruptive and depositional mechanisms of the 472 and 1631 eruptions complement those of section 3.2, with the objectives of defining the eruptive sequences, determination of isopachs and isopleths of deposits and determination of deposit volumes, quantification of time-wise distribution of eruptive mass discharge rates, and of drawing pyroclastic deposit facies maps. This work, if carried out in a thorough manner, is fully consistent with the objectives described in section 3.2.2.

4. The characterization of chemical and physical properties of discharged products of Vesuvius by means of different experimental methods will permit establishing thermodynamic phase diagrams of liquid, gas, and solid of pre- and post-eruptive conditions of magma. This objective is very ambitious if performed for different eruptions of Vesuvius, but required for the 1631 eruption as discussed in section 3.2.3.

5. The studies aimed at the understanding of magma-water interaction during the 1631 eruption are consistent with the requirements indicated in section 3.2.2.

6. The definition of the 1631 complete stratigraphic sequence and of the accompanying chemical, petrografical and isotopic variations, the definition of the influence of the magma withdrawal dynamics on the compositional variations of deposits, data gathering aimed at the estimation of magma chamber geometry, characterization of primary magmas, and definition of mixing and fractionation processes within the magma chamber are fully consistent with the research objectives indicated in sections 3.2.2, 3.2.3, and 4.

7. The understanding of primitive magmas and feeding system characteristics of Vesuvius is required for the definition of initial and boundary conditions as discussed in section 3.1.2.

Some additional general studies of Vesuvius worth pursuing include:

1. Post-plinian eruption behavior. The volcanological studies which address the post-plinian behavior of Vesuvius should have the objective of ascertaining whether the strombolian and lava effusions *always* follow the plinian and subplinian eruptions. For this purpose, the most urgent studies should address the periods after 79 and 472 eruptions.

2. Diapirs and magma supply. Santacroce (1991) proposed a magma supply to the Vesuvian system in the form of batches. It remains to be proven, however, how and where these batches are generated or controlled. The Sr-isotopic ratios of these batches may provide useful clues. It may be that the batches (if they exist) rise as diapiric bodies from the mantle, or that they are formed more superficially below the magma chamber after the chamber starts growing and the pressure in the chamber, and therefore in the feeding zone, decreases due to the opening of a conduit. A pressure decrease in the feeding region of Vesuvius after the conduit opens may produce large-scale melting and sustain the influx of new magma into the chamber until the magma in this region is exhausted.

3. The 472 Pollena eruption. A viable volcanic simulator should be able to *predict* the 472 plinian eruption of Vesuvius, when the simulation is initiated after the conduit closure following AD 79. For this purpose, it would be highly desirable to understand this eruption as thoroughly as the eruption of 1631. The volcanological, petrological, and isotopic studies aimed at the understanding of the 472 eruption should parallel those of 1631.

4. The prediction of plinian and subplinian eruptions of Vesuvius by a global volcanic simulator would be a significant step forward in volcanology and physical modeling of volcanological processes. The prediction of "small" volcanic activities (strombolian and lava effusion) subsequent to the conduit closure will, however, be more difficult. Nevertheless, a volcanic simulator must also be able to simulate the conduit closure phases of the volcano which will require testing of the predictions from simulations with field data. For this reason, more thorough volcanological, petrological, and isotopic studies of the eruptions following 1631 will also be required.

5. The prediction of future eruptions of Vesuvius by the simulator requires *anticipating future magma compositions.* For this purpose, thermodynamic parametrization studies of magmas is required whereby the composition-pressure-temperature phase diagrams need to be established. These studies are described in section 5.

3.3.2 Lava Flow Studies of Vesuvius

The 18th cycle of recent activities at Vesuvius terminated in 1944 and produced lava flows (Arnó et al., 1987; Scandone et al., 1986). Although lava flows at Vesuvius are not as hazardous as explosive eruptions, it is nevertheless required that a global volcanic simulator be able to predict the hazard potential of such flows. A research program aimed at developing lava modeling capabilities should include the appropriate geological studies pertaining to the morphological, rheological, and physical and chemical characteristics of past lava flows at Vesuvius. Such a program has been recently initiated for the lava flows at Etna within the Environment Program of the Commission of the European Communities.

The overall objective of the lava modeling program for Etna is to produce data and computer programs which can be used for assessing the volcanic hazard at Etna. The data will be used to verify the numerical models of magma and lava flows and will include: data pertaining to crack propagation with and without magma-sustained flow; data pertaining to dykes, effusion rates, temperatures, compositions and rheologies of past and new eruptions and correlation with dyke geometry, seismic data and petrology; and, local and general lava field data pertaining to ephemeral mouths, structures of crusts, tunnels, levees, and flow heads. The numerical models will include modeling of crack enlargements caused by the hydrodynamic, acoustic, and thermal effects of the uprising magma along the conduit, magma flow modeling with non-Newtonian rheology in the presence of melting/solidifying walls, thermoviscoelastic modeling of the conduit wall, thermoviscoelastic modeling of lava flow heads and crusts, and three-dimensional and global flow modeling of lava flows. The magma and lava flow models will be verified separately with past and new eruption data and the models will be integrated into a single numerical model or lava flow simulator able to simulate the magma ascent in conduits and lava flows during an eruption of Etna. A summary of this research program is included in the Appendix.

In the development of the lava flow simulator for Etna, it is anticipated that this simulator can also be used for lava flows at Vesuvius with some parametric changes to account for different lava properties and volcanic system. For this reason, we will not discuss further in this report the research requirements aimed at developing lava flow simulations at Vesuvius. These requirements should closely parallel those of Etna as described in the Appendix.

3.4 Concluding Remarks

The development of a global volcanic simulator for Vesuvius demands significant steps in volcanology, geology, geophysics, petrology, and experimental thermodynamics. The required advances include studies of deposits and their constituents to understand magma composition and tephra emplacement dynamics, construction of thermodynamic phase diagrams of liquid, gas and solids spanning the composition, pressure and temperature conditions of erupting magma, crystal kinetic studies involving several crystallizing minerals, and the development of experimental techniques to produce some of the required data.

4. Required Geophysical Studies

4.1 Overview of the Geophysical Studies of Volcanoes

Geophysical techniques of ever-increasing sensitivity are being applied today for the detection and mapping of deep volcanic structures. The determination of these structures is based on the variation of their elastic, electrical, magnetic, and gravitational properties. Since the geophysical techniques can detect only regions which differ sufficiently from others in some property (density, conductivity, magnetization, *etc.*), they are limited to nonhomogeneous and time-dependent media which makes them ideally suited for the investigation of volcanic substructures such as magma chambers. Of all known geophysical methods, the seismic wave technique has been proven of great utility in mapping volcanic substructures.

Seismic tomography employs techniques that yield three-dimensional images of complex zones of velocity and/or attenuation structures within the Earth using seismic waves from earthquakes or explosions (teleseisms). The technique models anomalous velocity and attenuation structures of P- and S-waves in volcanic areas using teleseisms. In the ACH technique (Aki et al., 1977), seismic waves from teleseisms arriving along different azimuths and distances illuminate the target volume and are recorded by an array of seismometers. Depending on the heterogeneities in the rock beneath the seismic array stations, the seismic waves may speed up or slow down, thereby generating a travel-time residual for each seismic ray at each seismic station. The large number of observed travel-time residuals are then inverted to compute two- or three-dimensional block models of velocity perturbations of the target volume with respect to a standard Earth model. The spatial resolving power of the technique is determined by the instrument spacing within the seismic array. The smallest size of the anomaly that can be resolved using teleseismic tomography is about 6 km (Iyer et al., 1990). This resolution can be improved in regions with local earthquakes; however, for the Vesuvian area, this technique is not applicable due to the apparent scarcity of these events (GNV, 1992). The above deficiencies can be reduced by a high-resolution tomographic imaging technique (NeHT) developed by Nercessian et al. (1984) which utilizes controlled explosions at sources. In the NeHT technique, a ring of large explosions is set off around the target area over which a dense array of seismographs have been deployed. The distances between the array and the shots are appropriately chosen to illuminate the volume to be imaged by the upward-traveling seismic waves. Practical constraints of explosive charges (less than 2000 kg) and size of the seismic array from 100-150 instruments with an average spacing of about 1 km provide a resolution of about 1 km in size. The NeHT technique has been used by Nercessian et al. (1984) (Mont Dore Volcano, France); Achauer et al. (1988) and Zucca and Evans (1992) (Newberry Volcano, USA), Evans and Zucca (1988) (Medicine Lake Volcano, USA), among others. The teleseismic tomography was used by Tryggvason et al. (1983) (Icelandic hot-spot volcanoes), Aster and Meyer (1988) (Phlegraean Fields, Italy), Stauber et al. (1988) (Newberry Volcano, USA), Dawson et al. (1990) (Long Valley Volcano, USA), among others. On the basis of teleseismic and high-resolution (NeHT) techniques, Iyer et al. (1990) concluded that the silicic volcanic centers in the western USA seem typically to have upper crustal bodies of low compressional-wave velocity. From this, it is inferred that these bodies are magma chambers containing few per cent of partial melt distributed throughout their volume. At the Newberry Volcano in particular, the high- and low-velocity anomalies observed from teleseismic and high-resolution tomographies, respectively, are associated with sub-solidus gabbroic remnants of basaltic intrusions on which is superposed a small silicic magma chamber (low-velocity body of Achauer et al., 1988) or recently solidified pluton (average attenuation zone of Zucca and Evans, 1992).

Temperature strongly influences the physical properties of volcanic materials which affect their electrical resistance. In addition to temperature, the porosity, fractures, pressure, pore fluid chemistry, water saturation, and mineralization within pores also affect the resistivity. The magnetotelluric, transient electromagnetic, Schlumberger resistivity, and other resistivity soundings data can be compared with drill hole data to determine rock types with various geoelectrical units. Gravity anomaly data are also useful for establishing different masses below a volcano, and together with seismic and electrical data can be used to construct a consistent *geophysical model* of a volcanic complex. As an illustration of the effective combination of geophysical data, Fig. 21 shows a geophysically determined model of Newberry Volcano in Oregon, USA.

4.2 Geophysical Research Needs at Vesuvius

As noted in section 2.3.2, a satisfactory geophysical model of Vesuvius does not exist and the best available geological model shown in Fig. 18 is incomplete and interpretative, especially in its central portion. In view of the potential danger of Vesuvius it is difficult to understand why the geophysics at Vesuvius has not been given the attention that it deserves, considering the availability of many geophysical tools which can be implemented efficiently, as attested by the worldwide efforts being made to geophysically map the volcanoes of far less importance. It should be noted, however, that a two-dimensional seismic tomography study at Vesuvius is being planned (Zollo, 1993); this study would preceed a three-dimensional high-resolution seismic study to be conducted in the future. The

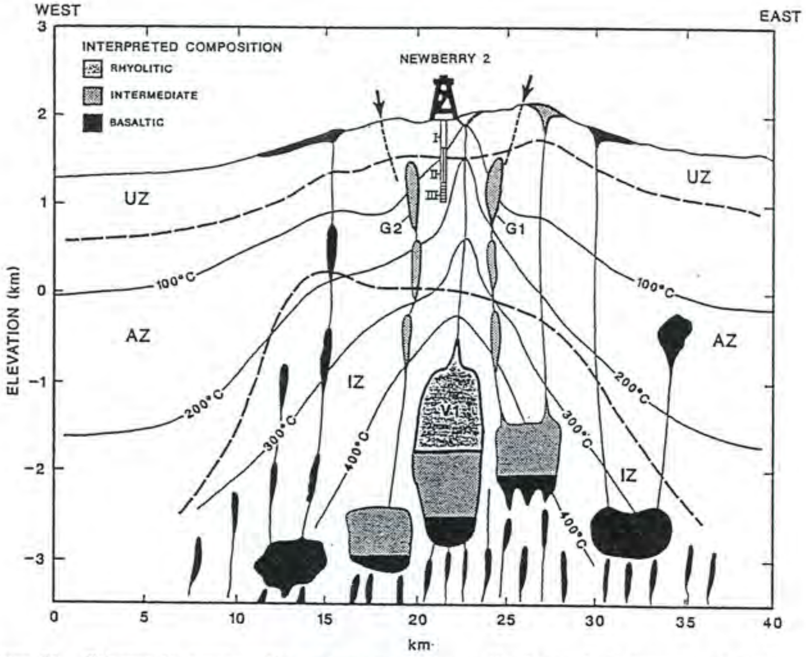

Figure 21. Schematic cross-section showing geophysically determined features of Newberry Volcano (Fitterman, 1988). The zones labeled UZ, AZ, and IZ (separated by heavy dashed lines) are based upon the electrical (Fitterman et al., 1988), seismic refraction (Catchings and Mooney, 1988), and gravity data (Gettings and Griscom, 1988), respectively. UZ zone consists of unaltered rocks composed of flows and tuffs characterized by high to very high resistivity (100-10 kΩm), low velocity (1.6 km/s), and low density (1300-2200 kg/m^3). AZ zone consists of altered volcanic rocks composed primarily of flows and tuffs with some feeder dikes and intrusions characterized by low resistivity (8-50 Ωm), intermediate velocity (4.1-4.7 km/s), and moderate density (2200-2500 kg/m^3). IZ zone consists of repeated intrusions containing numerous solidified feeder dykes, sills, and pod-shaped bodies and possibly a small magma body characterized by high resistivity (300 Ωm), high velocity (5.6 km/s), and high density (2500-2800 kg/m^3). The large pod V1 and feeder dykes G1 and G2 inside the inferred ring faults correspond to geophysical anomalies, whereas other intrusive bodies shown are conjectural. Body V1 corresponds to a low-velocity zone identified by seismic tomography and is thought to be molten (Achauer et al., 1988). The isotherms are based upon the hydrothermal modeling of Sammel et al. (1988). Drill-hole alteration zones are from Keith and Bargar (1988). The arrows show the locations of the inferred caldera ring faults. A recent high-resolution compressional wave attenuation tomography (Zucca and Evans, 1992) shows, however, that the low velocity zone identified above has only an average attenuation and that therefore it more closely resembles a recently solidified hot pluton than a magma chamber.

study will involve three explosive sources evenly-spaced along the 24 km NW-SE stretch which intersects the cone of Vesuvius. The experiment will involve a maximum of 100 receiving seismometers and it is argued that its resolution will be of about one kilometer. Assuming that the resolution of one kilometer can be achieved by the experiments of Zollo (1993), it may be possible to establish the existence of an anomalous body below Vesuvius but not to map the central portion of the volcanic system. (In section 6.2.2 it is argued that the magma chamber at Vesuvius during AD 79 eruption had a diameter of about 4 km.)

From the above it is clear that not enough effort has been invested, or is planned to be invested, into the geophysical soundings at Vesuvius to be useful for the construction of a global volcanic simulator. To remedy this situation it is suggested to carry out the following studies:

1. Realization of high-resolution and three-dimensional seismic tomography experiments aimed at identifying the structures below the central portion of the cone of Vesuvius and below the Somma caldera. The velocity and attenuation anomalies thus obtained should be employed to establish the rock type, porosity, amount of pore fluids and their state, and degree of melting. Since it is known that partial or total melting of a rock causes its characteristic wave velocity to decrease and its characteristic attenuation to increase (Mavko, 1980) and there may be several such regions at Vesuvius (section 2.3.3), the experiments should be designed very carefully to map as many small partial melt bodies as possible with today's technology. A high resolution seismic tomography at Vesuvius should also establish the extent of fracturing and the nature of these fractures below the central portion of the cone of Vesuvius. This information is vital for the proper modeling of the volcanic substructure and for establishing the structural stability of the cone (section 6.3). As indicated in section 3.1.2, geophysical studies are also necessary to ascertain P- and S-wave velocities in the feeding system to establish possible minerals giving rise to the primary magma.
2. Evaluation and establishment of gravity data. Bouguer gravity anomalies should be calculated from different gravimetric surveys conducted to date in the Vesuvian area. Cassano and La Torre (1987) used the gravity data until 1979. It is also necessary to *evaluate* the gravity data, and, based on this evaluation, conduct new campaigns which may reduce uncertainties and resolve the central portion of Vesuvius with more detail.
3. Evaluation and establishment of magnetometry data. The work associated with this task parallels the one associated with the evaluation of gravity data, with the objective being the production of a high-resolution three-dimensional magnetic map model of the Vesuvian area (see Cassano and La Torre, 1987).

4. Evaluation and establishment of electrical data. Three different electrical methods should be used to characterize more completely the electrical structure of Vesuvius: magnetotelluric, transient electromagnetic, and Schlumberger resistivity. The use of Schlumberger resistivity at Vesuvius is reported by Cassano and La Torre (1987).
5. Establishment of a *geophysical model* of Vesuvius. The seismic tomography, gravity, magnetometry, and electrical data should be integrated to produce a geophysical model of the Vesuvian area. Such a complete integration of all geophysical methods is necessary before using this model in the construction of a complete *geologic model* of the volcanic substructure (see section 3.1.2). By integrating multiple methods and maximizing their individual strengths, a geophysical model of Vesuvius may be obtained that is more accurate and consistent with all types of data than it would be obtainable from any one method alone. Fitterman (1988) discusses, for example, how several different geophysical studies can be integrated into producing a geophysically consistent model for Newberry Volcano.

4.3 Concluding Remarks

The geophysics at Vesuvius has been lacking considerably behind the volcanological and petrological studies. Perhaps this has been caused by the apparent inactivity of the volcano or perhaps not enough has been done to promote its potential danger. Whatever the reason, the geophysics at Vesuvius should get moving quickly and seriously.

5. Required Thermodynamic Parametrization Studies of Magmas

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Università "La Sapienza" di Roma, Roma, Italy.

5.1 Overview of Magma Parametrization Studies

The Vesuvian volcanic system has displayed a wide variety of eruption styles which can be associated with the relationships between the mechanical, thermal, and chemical characteristics of rocks and magma in different regions of the volcanic system. The supply of magma into the Vesuvian system may be characterized by periods involving hundreds to thousands of years, depending on the time- and length-scales of the transport processes, which will be very different for fracture- and diapiric-dominated transport. The melt transport and thermochemical interactions with country rocks may produce changes in the chemical characteristics of magma which may in turn produce a feedback effect which modifies the melt transport along the geothermal gradient of the Vesuvian magma supply system. There will thus be a close relationship between the chemical and physical processes of the melt extraction process (Nicolas, 1986). Magma mixing, convection, crystallization, and assimilation of surrounding rocks also involve different time- and length-scales which can produce a feedback between magma composition and thermofluid-dynamic processes in magma chamber. During the opening stages of an eruption, the magma ascent times may be very short (Ramos and Dobran, 1993) which may prevent thermodynamic equilibrium conditions of magma to be maintained. The well-established thermodynamic equilibrium methods for calculating the gas exsolution and other magma properties (Nicholls, 1980; Ghiorso et al., 1983; Papale and Dobran, 1992a) may be in error. It should thus be clear that when the time- and length-scales of macroscopic thermofluid-dynamic and microscopic molecular relaxation processes become of equal importance, the kinetic or nonequilibrium effects may influence the relationship between magma composition, pressure, and temperature, and change the physical and rheological properties of magma.

The thermodynamic parametrization studies of magma should have the objective of parametrizing the Vesuvian magmas in terms of composition, pressure, and temperature where the time-scale of molecular relaxation processes may be important. In the magma supply region and magma chamber, the time-scale of magmatic processes is large and the effect of molecular relaxation processes in determining the relationship between magma composition, pressure, and temperature should not be important. However, in an emptying magma chamber and during magma ascent along the conduit(s), the molecular relaxation times associated with gas exsolution may be sufficiently large in comparison with the magma transit times in these regions to produce a significant effect upon the eruption dynamics. For these reasons, the parametrization studies of Vesuvian magmas should involve the spatial and temporal characteristics associated with macroscopic magmatic processes determined from thermofluid-dynamic modeling.

5.2 Parametrization of Magma Composition

The simultaneous parametrization of magma composition, pressure, and temperature for the same unit mass of a volcanic sample should involve the construction of thermodynamic phase diagrams relating the compositional variables with pressure and temperature. The compositional variables are made of silicate components consisting of major, minor, and trace elements, and of volatile components consisting of H_2O, CO_2, Cl^-, F^-, BO_3^-, SO_2, *etc.* Whereas the parametrization of the compositional variations associated with silicate components is a classical petrographic argument (starting from Bowen, 1928), the volatile components variations with pressure and temperature in the melt has only recently been established (Carmichael et al., 1974; Dolfi and Trigila, 1978; Nicholls, 1980; Ghiorso et al., 1983; Spera, 1984; Papale and Dobran, 1992a), since this necessitates information on the relationships between structure and composition of the silicate melt and on the solid solutions of the phenocrysts in equilibrium with the same melt.

The required parametrization studies of Vesuvian magmas for the purpose of constructing a global volcanic simulator for Vesuvius are those pertaining to the definition of initial and boundary conditions, and those associated with reference eruptions used for verifying the predictions of the simulator. As discussed in section 3.1.2, the initial and boundary conditions of magma in the magma supply region of Vesuvius and magma differentiation region or magma chamber are required for the input to the simulator to initiate the simulation process. These studies should involve those compositional ranges which span the *uncertainty limits* of compositions defined by the geophysical studies of P- and S-wave velocities, thermofluid-dynamic constraints related to magma ascent along the geothermal gradient, petrologic constraints of possible rock types and metamorphic reactions, geochemical and isotopic constraints obtained from the eruption products immediately before the conduit closure following the AD 79 eruption of Vesuvius, magma eruptibility constraints such as that defined in section 6.2.2, *etc.* It should be stressed that the proper determination of initial and boundary conditions for magma compositions should involve some physical modeling in the magma supply and storage regions of the volcano, since the macroscopic evolution of the magmatic systems, together with geophysical, petrological, and other constraints, will also define the proper magmatic compositions. The required magma composition studies related to the 1631 eruption of Vesuvius are discussed in section 3.2.3 where it is pointed out that magma studies should be undertaken to establish its properties *during the entire course* of the 1631 eruption. These studies should be carried out on all significant volcanic products of the 1631 eruption for the purpose of ascertaining the compositional ranges during the eruption. The previous studies of pumice samples pertaining to plinian and pyroclastic flow phases (Rosi et al., 1992) are not sufficient for detailed reconstructions of magmatic events and for adequately verifying the results from the simulator.

The determination of compositional variables of selected samples of magmatic products should be performed after the geochemical, petrographical, and mineralogical studies of diverse lithotypes have been performed. These analyses would then permit to discriminate between possible differentiation processes which influenced or may influence the physical and chemical characteristics of the magmatic melt. The evaluation of differentiation processes associated with fractional crystallization have been widely discussed. Given the initial composition of the magmatic melt, the mass balance processes allow for the establishment of the percentage of solid which fractionates as one or more crystalline phases (for example, *Xl*-frac, Stormer and Nicholls, 1978). Such an approach may also include the concentration of minor or trace elements, if the partition coefficients between liquid and crystalline phases are known (Villemant et al., 1992). More suggestive, but of more limited use, is the program *magmodel* (Nathan and Van Kirk, 1978) which simulates the fractional crystallization of mineral phases from a magmatic melt based on the phase relations at atmospheric pressure in an anhydrous system of nine components. Given the initial melt composition, the final composition can then be generated automatically by the progressive subtraction of small quantities of fractionated solid in an iterative process which generates the corresponding compositions of the differentiated melt. A different approach from the one described above is that of Pearce (1968). This method allows for the verification of the magmatic differentiation process which controls the compositional variations of the samples. The method is based on the assumption that if different compositions are produced by a fractionation process, then there are chemical elements which are not involved in the crystallization process and which conserve the global mass. These elements can be identified by specific methodologies and represent the normalizing factor through which geochemical variations between different lithotypes can be analyzed. This method allows for the construction of petrogenetic diagrams (*paragenetic diagrams* (Fig. 22) for the definition of fractionated paragenesis, *discriminating diagrams* (Fig. 23) to evaluate the importance of respective phases in the resultant paragenesis) which are useful for the definition and quantification of the magma fractionation processes (Stanley and Russell, 1989; Ernst et al., 1988; Trigila and De Benedetti, 1992). Limits of this method are due to the analytical error of the conservative element due to its low abundance, error associated with the determination of the composition of the fractionating phases, error associated with the estimation of the conservation of the element, and finally error due to the dissolution of silicate components in the volatile phase.

The total pressure and temperature of a silicate melt can be obtained on the basis of chemical equilibrium conditions together with the assumption of a regular solution behavior for the liquid and crystalline phases. There are several methods which may be employed for these calculations (Carmichael et al., 1977), which generally consider the equilibrium relations between the same component in various mineral phases. A limit of these methods is, however, that it is difficult to evaluate on a petrographic basis the equilibrium assumption. More recent methods (Trigila et al., 1992) avoid this problem by: (1) considering equilibrium relations for two or more components of the same phase (for example, Ab and An in plagioclase), and (2) using the composition of experimentally obtained crystalline phases in the calculation of activities of components of the silicate melt. Because of the intratelluric paragenesis of the Vesuvian recent lavas consisting

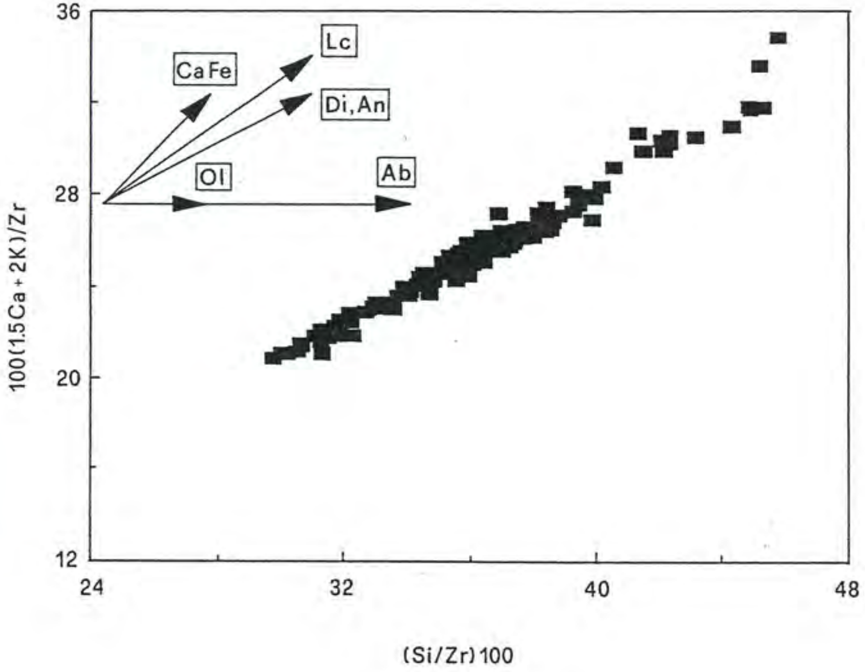

Figure 22. Fractional differentiation in the historic lavas of Vesuvius: example of a *paragenetic diagram* of Pearce (Trigila and De Benedetti, 1992).

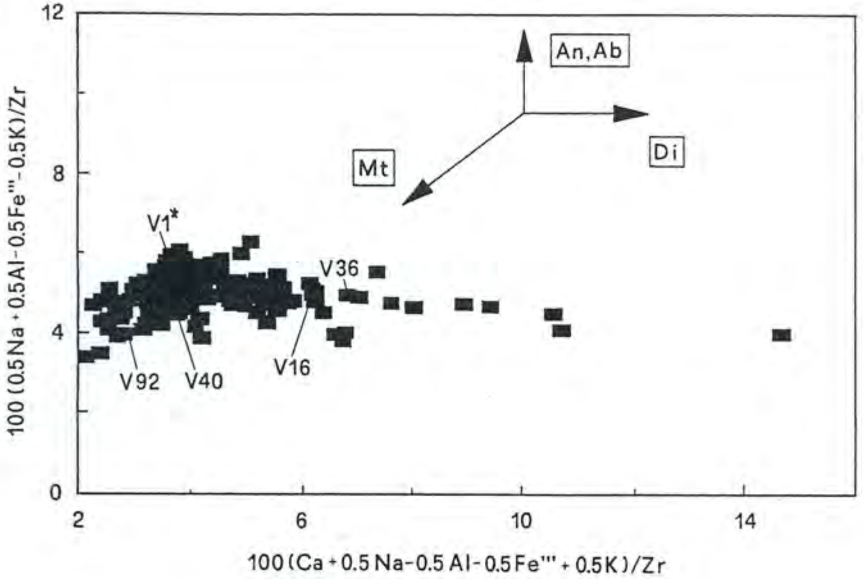

Figure 23. Fractional differentiation in the historic lavas of Vesuvius: example of a *discriminating diagram* of Pearce (Trigila and De Benedetti, 1992).

essentially of ubiquitous pyroxenes (and leucite) and occasional plagioclase and olivine, it is not possible to build up intersecting isoactivity curves using these minerals, causing therefore considerable uncertainty in the pressure-temperature estimate for the crystal-liquid equilibria. In order to overcome this difficulty it will be necessary to establish an additional reaction involving a second component in the clinopyroxene phase.

The abundance of volatiles in magma and their variations during crystallization can be studied by analyzing the *magmatic inclusions*, provided no leakage has taken place during the geologic time. The destructive techniques commonly used for extracting volatiles are based on a large number of inclusions with the shortcomings: (1) only bulk composition of a great number of inclusions can be obtained, (2) samples of mineral separates cannot be made very pure, (3) inclusions from different generations cannot be distinguished, and (4) a considerable portion of volatiles may undergo chemical decomposition during the high temperature extraction process in the laboratory. Recent techniques for the determination of volatiles involve: (1) estimation of the total amounts of volatiles (mainly H_2O) dissolved in the glass by ion probe, (2) electron microprobe analysis of F, Cl, S, and P contained in silicates (now present as glass) in magmatic inclusions, and (3) laser Raman microprobe determination of volatiles in shrinkage gas

bubbles of magmatic inclusions or in the contemporaneous fluid inclusions in igneous minerals (Clocchiatti, 1975; Roasaco et al., 1975; Clocchiatti and Metrich, 1984; Linqi et al., 1991). Using the Raman microprobe analysis in conjunction with electron microprobe analyses, Linqi et al. (1991) showed that it is possible to establish the initial conditions of volatiles in magmas provided an intelligent use of the quantitative thermodynamic approach is employed in conjunction with experimental data. Such an experimental-theoretical petrologic approach has the potential to provide a great deal of information on the crystallization processes in magmas and for the reconstruction of magma chamber activities.

5.3 Determination of H_2O, CO_2, and Cl^- in Magmas

Volatile components are always present in magmas. The principal volatile component is H_2O, but other components, such as CO_2, F^-, Cl^-, and SO_2, may also be present in significant amounts in different parts of the Vesuvian system. The composition and concentration of volatiles dissolved in melt play an important role in determining its chemical and physical properties. Among these properties are the phase relations (Fig. 24), liquidus temperatures , distribution coefficients of the elements between the crystalline and liquid phases, and the rheological properties (viscosity, density, diffusivity, thermal conductivity). The knowledge of the modalities of dissolution of volatiles in silicate melts at Vesuvius is essential for an understanding of the petrogenesis of igneous rocks in the magma supply, magma differentiation, and magma ascent regions. It should be stressed, however, that the correlations often made in the past between the distribution of volatiles in the rock and that in magma *may not be utilized* even in those particular cases for which relatively fast cooling of the melt from the temperature and pressure of magma chamber to the atmospheric conditions takes place. In fact, because different volatile species are dissolved in the melt with different kinds of bonding forces, depending of their composition, pressure, and temperature, their exsolution is selective. Moreover, the estimation of the residual volatile contents in the rock may not give any information about the evolution modalities of the magmatic system from the source to the surface, which may evolve in both closed and open system conditions. In the latter case, the magma may be subjected to the addiction or subtraction of volatiles from the environment which changes the magmatic volatile concentration during its ascent to the surface of the Earth (Dolfi and Trigila, 1978; Trigila, 1990; Trigila et al., 1992). It thus becomes important to determine the solubilities of volatile species of different kinds of Vesuvian magmas along *all possible pressure-temperature paths* from the magmatic source region to the surface of the Earth. By knowing these paths, it is then possible to establish the depths at which a silicate melt begins exsolving different volatiles as an independent phase.

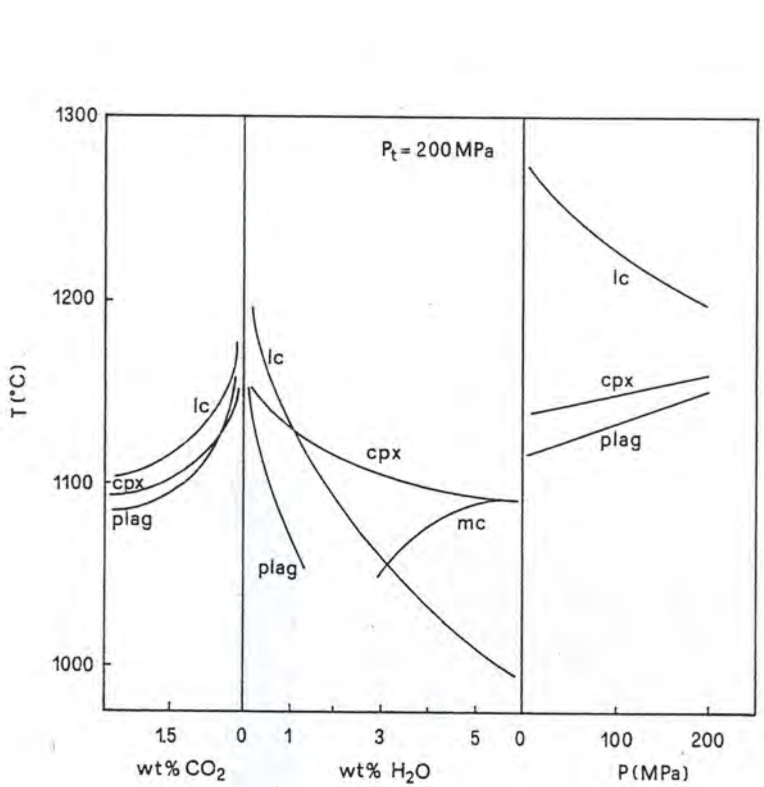

Figure 24. Compositional and concentrational influence of volatile species on the phase relations of the tephritic leucitite system representative of the magmas during the eruption of Vesuvius in 1944.

Determination of H_2O

Past theoretical and experimental investigations were employed to establish the dissolution mechanisms of water in the synthetic and natural silicate systems, and the establishment of solubilities at different pressure and temperatures. Based on the infrared (IR) spectroscopy, nuclear-magnetic-resonance (NMR) analysis, and H_2 manometry, Stolper (1982a,b) showed that part of H_2O is dissolved in the ionic form and part in the molecular form. Up to about 3 wt% of H_2O the ions of OH^- prevail, whereas at about 4 wt% there is a kind of equilibrium between the two species. For water contents greater than about 4 wt% the molecular form of H_2O dominates. The solubility is a negative function of temperature, since in the range from 100-300 MPa it decreases from 0.2-0.3 wt% of H_2O for every 100°C temperature increase (Burnham and Jahns, 1962).

The total H_2O concentration and the modalities of its dissolution are a function of the composition of the liquid system. The solubility appears to increase with the silica content (picrite < nefelinite < basalt < andesite < granite < pegmatite) (Oxtoby and Hamilton, 1978). However, McMillan and Holloway (1987) found that the solubility regularly increases with decreasing silica content in binary and pseudobinary silicates, and along the silica-nepheline join. A similar result was also found by Papale and Dobran (1992a) for magma compositions similar to those that erupted at Vesuvius in AD 79. Furthermore, it has also been shown that the solubility of H_2O in the phonolitic magmas is greater than in the granitic magmas (Kogarko et al., 1977). Other studies emphasize the role of aluminium (Dingwell et al., 1984) and the role of alkaline cations in modifying the water solubility. There is still an open question regarding the existence and stability of different M-OH complexes in silicate melts, the effect of the double role of aluminium as a network-builder and network-modifier, and whether the role of the alkaline metals and rare elements are important in modifying the dissolution of water in the silicate melt (Stolper, 1982a; Mysen and Virgo, 1986; Mysen, 1988; Silver et al., 1990).

The solubility of H_2O in silicate melts can be experimentally determined in the high pressure and temperature autoclaves with different analytic techniques on samples with compositions representative of silicate melts. The most common techniques involve chemographic or phase equilibria analysis (Burnham and Jahns, 1962; Fenn, 1973; Voigt et al., 1981), weight loss technique (Goranson, 1931; Bowen and Tuttle, 1950; Oxtoby and Hamilton, 1978), differential thermal analysis (Eggler and Rosenhauer, 1978), H_2 fusion manometry (Dingwell, 1984), Karl Fish titration, and IR spectroscopy and NMR (Stolper, 1982b).

The determination of the effective quantity of dissolved H_2O in the magmatic melts requires first of all the knowledge of the reference pressure and temperature values of the magma chamber or magma source region (Fig. 25) (see previous

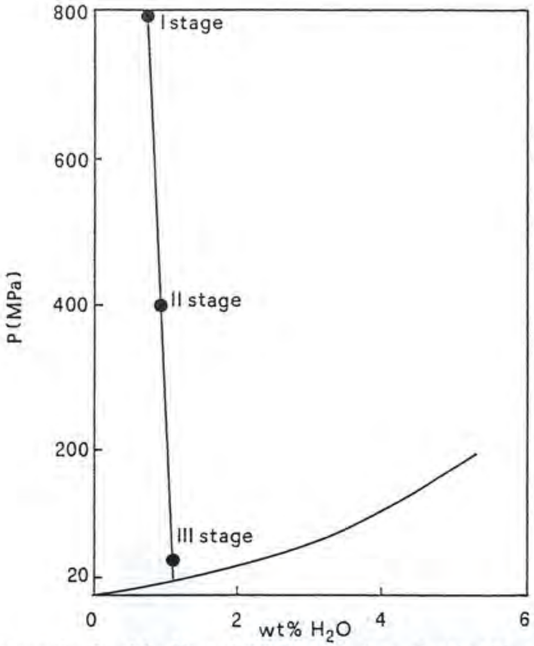

Figure 25. H_2O saturation level for V_1 tephritic leucitite from the 1944 Vesuvius eruption. The depth of the saturation level can be inferred from the intersection of the H_2O solubility curve with that of estimated water contents of the magma for I, II, and III crystallization stages (Dolfi and Trigila, 1978).

section). The methods by which this quantitity may be evaluated involve: (1) the experimental calibration as a function of H_2O of some compositional parameters of the crystalline phases in equilibrium with the melt, (2) thermodynamic calculations to extrapolate the energetic parameters of the standard state of exsolved and dissolved water to different pressures and temperatures, or (3) a combination of both.

The first approach was followed by identifying the phases (widely diffused in the process of the magmatic crystallization) whose compositions may change with the dissolved H_2O content without drastic variations in their stability field. Experimental research on the solid solutions of clinopyroxene in the Vesuvius lavas (Dolfi and Trigila, 1978) have identified $CaAl_2SiO_6$ as the component of clinopyroxene whose natural logarithm of the molar fraction linearly varies with pressure and H_2O dissolved in the melt. The obvious limitation of this approach is in the need for an experimental investigation of these relations for any chemical system under consideration. A way to perform this evaluation through thermodynamic computations consists in considering H_2O as an added component that acts as a dilutant for other components in the melt. By considering the solid-liquid reactions that involve different phases, like feldspars, whose stability field varies considerably with H_2O dissolved in the melt, it is sufficient to perform calculations by considering different quantities of H_2O in the melt (Carmichael et al., 1977). The relationship between the composition of feldspars and dissolved H_2O content at given values of pressure and temperature permits the determination of the dissolved water content in the melt, when compared with the pressure and temperature obtained through reactions whose components are not sensitive to the amount of H_2O dissolved in the melt. In particular cases of the break-down of a hydrous mineral (usually mica or amphibole), when it is possible to assume that the fugacity of water in magma is buffered by the presence of the hydrous phase, it is possible to obtain the water content for a given pressure and temperature (Carmichael et al., 1977). This method has, however, a restricted applicability, since the hydrous minerals do not usually belong to the stable paragenesis at atmospheric pressure, and because the relationships between activity and composition for most of the components that constitute these phases still need to be determined.

The second approach of water solubility determination is based on a thermodynamic formulation in which the particular physical and chemical conditions of magma and volatiles are accounted in terms of the deviation from a standard state (Nicholls, 1980; Papale and Dobran, 1992a). The advantage of such an approach consists in utilizing only the anhydrous composition of magma to establish the maximum dissolved water content at different pressures and temperatures which can be expressed by analytical expressions suitable for implementation into the simulator. Such a model formulation requires many parameters (standard state conditions, partial molar volume and activity of water in melts of various compositions, *etc.*) which necessitate a large body of experimental data which at present are only partially available, and establishes only the *maximum* dissolved water content. The future work at water dissolution modeling should incorporate a sufficiently large data base to span all possible variations of Vesuvian magmas and incorporate other volatile species (at least CO_2 and Cl^-) and account for the molecular relaxation processes during rapid magma ascent times.

Determination of CO_2

The genesis and evolution of magmas at Vesuvius are associated with a fluid phase where CO_2 is a minor but crucial component (Trigila and De Benedetti, 1992). The quantitative chemical and physical effects of CO_2 on magma properties are not yet known, especially at high pressures and temperatures and in the presence of other fluid phases. A complete understanding of the processes, such as the phase equilibria, vesiculation, bubble growth, magmatic explosivity, and their implications in the gas evolution at atmospheric pressure, needs an estimation of the solubility of CO_2 in the melt and the knowledge of its speciation in the silicate structure. Infrared studies established that in some silicate melts there is an equilibrium between the carbonatic anions (CO_3^{2-}) and molecular CO_2 (Fine and Stolper, 1985; Stolper et al., 1987). In these studies, however, there is no agreement on the proportions of the species and the details of the *chemical environment* surrounding the carbonatic ion. The CO_2/CO_3^{2-} ratio increases with the silicic content along the bond $NaAlSiO_4$-SiO_2 (Fine and Stolper, 1985) where the presence of the molecular CO_2 appears to be tied to the dimensions of voids within the liquid structure.

The solubility of CO_2 in silicate melts is more than an order of magnitude less than that of H_2O (Eggler and Rosenhauer, 1978; Spera and Bergman, 1980). It varies as a function of the degree of melt polymerization and reaches a maximum in the basic alkaline melts with values which are three times greater than those in the feldspar liquids. The fundamental aspects of the CO_2 dissolution in magmas were analyzed by Spera and Bergman (1980) who proposed a model for the determination of CO_2 solubility in a melt at a given pressure and temperature. The solubility of CO_2 in the hydrous melts is far greater than in the anhydrous melts; in liquids with diopsidic composition it varies between 2 wt% at 2GPa in anhydrous conditions to 9 wt% when the melt is saturated in H_2O+CO_2 (Eggler and Rosenhauer, 1978). The mixture of H_2O and CO_2 in a melt appears to be largely non-ideal. Clearly, the evaluation of the *ideality* of the mixing properties in the fluid phase is a critical element in the determination of the solubility of CO_2 under the conditions of *mixed volatiles.* A possible situation during the magma ascent at Vesuvius is that the magma is saturated with respect to CO_2 and not saturated with respect to H_2O, with the result being that the volatile phase is prevalently constituted by CO_2 whereas H_2O is prevalently concentrated in the liquid phase. This situation is verifiable through the thermometric analysis of CO_2 fluid inclusions and of the melt containing H_2O in the intratelluric crystal phases.

The composition of the volatile phase may also be obtained from the experimental analysis of the *solidus* temperature of the system which at different pressures is a function of the $CO_2/(CO_2+H_2O)$ ratio (Fig. 26). Moreover, the composition of the vapor phase which exsolves from liquid is different if the magmatic system during the magma ascent is closed or open. In the former case, the proportions between the liquid and crystals vary, whereas the composition of the volatile phase does not significantly change until the liquid becomes saturated in H_2O. In the open system case, the volatile phase enriched in CO_2 diffuses in the surrounding rocks and the magma may rapidly loose its CO_2 content. The gradual change of CO_2 from the liquid to the gas phase, and from this to the surrounding rocks produces the solidus temperature decrease which delays the exsolution of H_2O from the melt (due to crystal melting) until the pre-eruptive conditions have been reached. The solubility relations of H_2O and CO_2 in silicate melts are presented in Fig. 27.

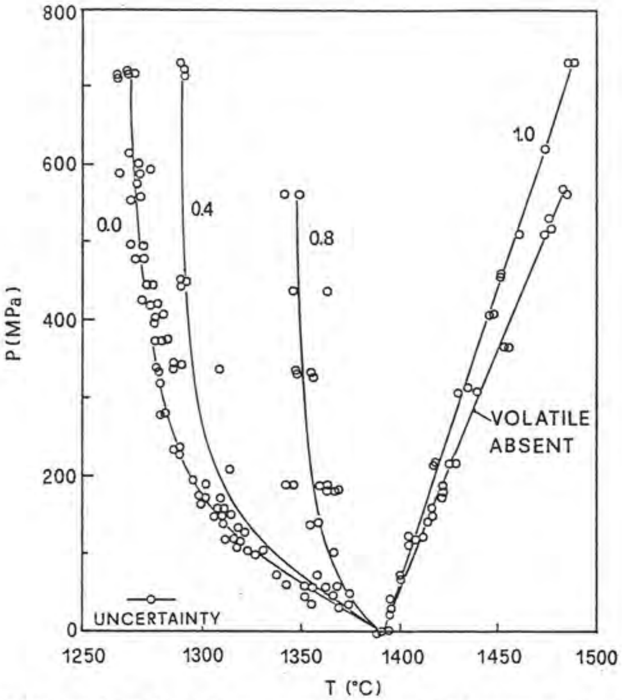

Figure 26. Melting of diopside in the presence of CO_2 and H_2O vapor and in the absence of volatiles, as determined by DTA experiments. Numbers indicate the vapor composition (molar $CO_2/(CO_2+H_2O)$) of the solidus isopleths. Each circle represents one DTA measurement with only peak temperatures being recorded (Eggler and Rosenhauer, 1978).

From the above, it is clear that the present knowledge of the CO_2 solubility is not adequate for the modeling of the exsolution of CO_2 during the magma ascent at Vesuvius from the magmatic source to the surface of the Earth without the introduction of assumptions that the magma is saturated in CO_2 and that the magma ascent takes place in a closed system. The solubility of CO_2 in the melt is also a function of the dissolved H_2O, and it is thus necessary that these solubilities at different pressures and temperatures be evaluated simultaneously.

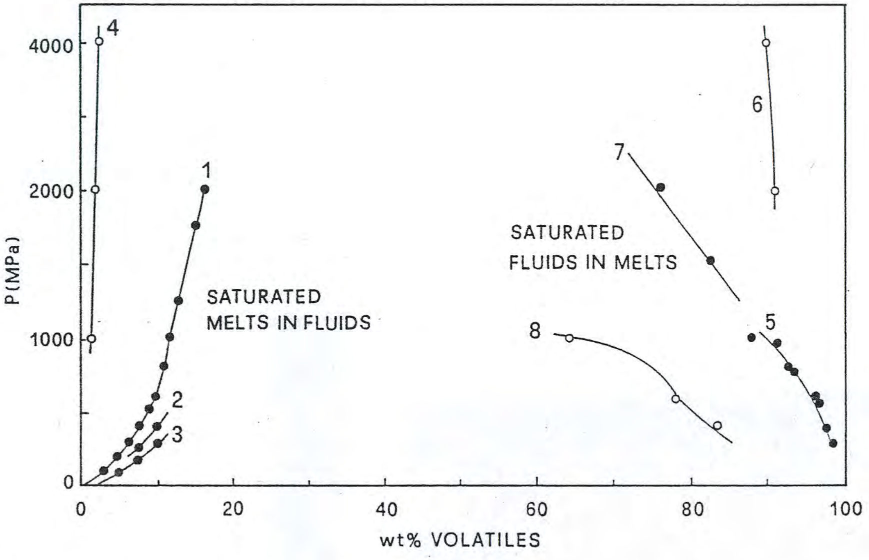

Figure 27. Solubilities of fluid components H_2O and CO_2 in silicate melts, and of melts in fluids (Trigila et al., 1992). The numbering of curves corresponds to: 1. Solubility of H_2O in tholeitic melts at pressures less than 80 MPa, 2. solubility of H_2O in synthetic tephritic melts, 3. Solubility of H_2O in K-trachitic melts, 4. Solubility of CO_2 in albitic melts, 5. Solubility of a granitic melt in H_2O, 6. Solubility of a diopsidic melt in H_2O, 7. Solubility of an andesitic melt in H_2O, and 8. Solubility of a nephelinitic melt in H_2O.

Determination of Cl^-

A systematic study of the historical products of Vesuvius (Belkin et al., 1992) demonstrates that the concentration of Cl^- in the melt is very abundant and that in less porphirytic types reaches up to 6000 ppm (parts per million). Experimental crystallization studies of these compositions indicate that if the melt is anhydrous then Cl^- is distributed almost exclusively in the melt (Trigila and De Benedetti, 1992) and reaches concentrations up to 10000 ppm, whereas it is concentrated in the fluid phase if the melt contains H_2O (De Vivo, personal communication).

The distribution of Cl^- between silicate melt and exsolved fluid phase is also a function of pressure and temperature and of its total concentration (Webster, 1992). The reduced solubility of Cl^- with increasing pressure is probably caused by an increased stability of aqueous complexes with respect to those of alkaline metals in the melt. However, the direct correlation between the solubility and temperature - a behavior opposite to water - may be caused by the large molecular dimensions of Cl and thus of the large energetic cost necessary to force the molecule into the cavities of the structure (Webster, 1992). In spite of the negative concentrational dependence of Cl^- with pressure it was demonstrated, through chemical studies of fluid inclusions in phenocrysts and lava glasses, that Cl^- degasses with H_2O and other volatiles during the decompression of an ascending magma (Kovalenko et al., 1988). Given the large solubility difference between H_2O and Cl^- in a silicate melt, the effect of Cl^- on the solubility of H_2O can be neglected, whereas the effect of the aqueous phase is not negligible on the solubility of Cl^- in the melt. On the basis of the above experimental data, it follows that the role played by Cl^- can be a determining factor in signaling the compositional and concentrational variations of volatile phases in magma, which can be used as means for a better characterization of parameters which control the ascent of magma and behavior of volatiles.

5.4 Concluding Remarks

The discussed methods for the parametrization of variables which control the genesis and ascent of magma associated with historical eruptions of Vesuvius bring about the following considerations.

The parametrization of compositional variations of eruptive systems gives an information on the evolution of these systems but not on their initial composition (for partial melting of source rock). Such a parent composition may be obtained by the inverse extrapolation of the evolving process and verified experimentally at given pressures, temperatures, oxygen fugacities, and volatile compositions. It is believed that the fundamental differentiation process is represented by the solid-liquid fractionation, but other variations of silicate melt composition associated with the addition and subtraction of volatiles cannot be neglected. The evaluation of other differentiation processes may be achieved experimentally by determining the solubility of the major magmatic species which can be dissolved in volatiles at pressures and temperatures which control the solid-liquid fractionation.

The equilibrium pressure and temperature between the components of intratelluric crystallization phases (or of source rock) and of the same phases in magmatic melt can be considered correct if the equilibrium assumption is satisfied. This is achieved if the components in the solid-liquid reactions belong to the same phase and if it is possible to verify accurately the liquid composition in equilibrium with solid phases (for example, by determining the compositions of phases in a pressure-temperature-composition space, or more simply by analyzing the eventual *melt inclusions*). In Vesuvian lavas, the only phase which constantly participates in the crystallization process is clinopyroxene. Within this phase, only one reaction related to the diopside is actually available and it is thus necessary to activate a second reaction for the clinopyroxene for simultaneous determination of pressure and temperature based exclusively on this phase.

In spite of many experimental results on the solubility of volatile species in silicate melts as a function of pressure, temperature, composition, and oxygen fugacity, it is not yet possible to employ these results for the parametrization of magmatic variables in terms of *mixed volatiles* (at least H_2O and CO_2). In fact, during the heterogeneous equilibrium calculations at pressures and temperatures of volatile species in the melt it is necessary to consider the mixing energetics of the species and the effects of these species on the solubiliy in silicate melt. This is the case in point for Vesuvius where the composition of intratelluric phases suggests a magmatic evolution which is controlled by mixed volatiles, and in which CO_2 plays a determining role. Clearly, the proper determination of the properties of mixing with the degree of nonideality of volatile species (at least H_2O and CO_2) is crucial in the determination of the solubility of CO_2 in mixed volatiles conditions. Once it becomes possible to establish the $CO_2/(CO_2+H_2O)$ relationships in liquid and volatile phases for given pressure and temperature paths followed by the ascending magma, it will then become possible to calculate the exsolution of H_2O and CO_2 from magma during its ascent.

Io mi volsi da lato con paura
D'esser abbandonato, quand'io vidi
Solo dinanzi a me la terra oscura.

Dante, perchè Virgilio se ne vada,
Non pianger anco, non pianger ancora!
Chè pianger ti conven per altra spada.

Guardaci ben! Ben son, ben son Beatrice
Come degnasti d'accedere al monte?
Non sapei tu che qui è l'uom felice?

Dante (1265-1321), purg. III, XXX.

Nature, and Nature's Laws lay hid in Night
God said - Let Newton be! and All was light.

Alexander Pope (1688-1744)

6. Physical, Mathematical, and Computer Modeling Requirements

6.1 Overview of the Modeling Approach

The prediction of volcanic eruptions and production of realistic hazard-zonation maps of Vesuvius requires global modeling of the volcanic system. This modeling should adequately resolve the thermofluid-dynamic processes of magma mixing, differentiation, and crystallization in the magma chamber, changes in magma chamber geometry with time due to inflow and outflow of magma and changing stresses of surrounding rocks, magma ascent along the conduit and interaction with conduit's walls, structural response of the volcanic edifice to magma chamber and conduit processes, and distribution of erupted products in the atmosphere and along the flanks of the volcano. The global model should not only simulate well all of the relevant physical processes below and above the surface, but also simulate them *efficiently*, for, otherwise, a global volcanic simulator cannot serve its intended purpose. The physical simulation requirements of magma, country rock, and pyroclastic products during the repose and eruption of Vesuvius require special considerations in modeling and computer implementation of numerical algorithms.

The volcanic system of Vesuvius may be schematically illustrated as shown in Fig. 28 during an open-conduit condition, where different parts of this system can be characterized by some unique properties or characteristic physical phenomena. For this purpose, it is possible to envisage a magma chamber domain, conduit domain, soil or country rock domain, and pyroclasts domain. Melt which is segregated from rocks in the feeding system of Vesuvius ascends upward and is collected into a magma chamber where the thermofluid-dynamic processes of convection, crystallization, and magma differentiation play a central role in defining the evolution of the chamber. The magma chamber domain thus consists of an open system for mass, momentum, and energy transfer where multiphase and multicomponent flow phenomena take place. The magma chamber evolution also depends on the magma ascent characteristics in the conduit and state of stress of the surrounding rocks. These rocks or soil domain can behave elastically, viscoelastically, or viscoplastically, depending on the local pressure, temperature, and degree of fluid saturation. The conduit domain can be characterized by propagating fractures induced by magma and conduits wherein the magma may exsolve the dissolved gases, fragment into pyroclasts, and interact with conduit walls and surrounding aquifers. The pyroclasts domain involves mixing of tephra with the atmosphere and interaction of pyroclastic products with the topography of Vesuvius. Due to the complexity of physical phenomena, each domain's model is very complicated and must be optimized for the simulation of the relevant phenomena and for the implementation on a computer.

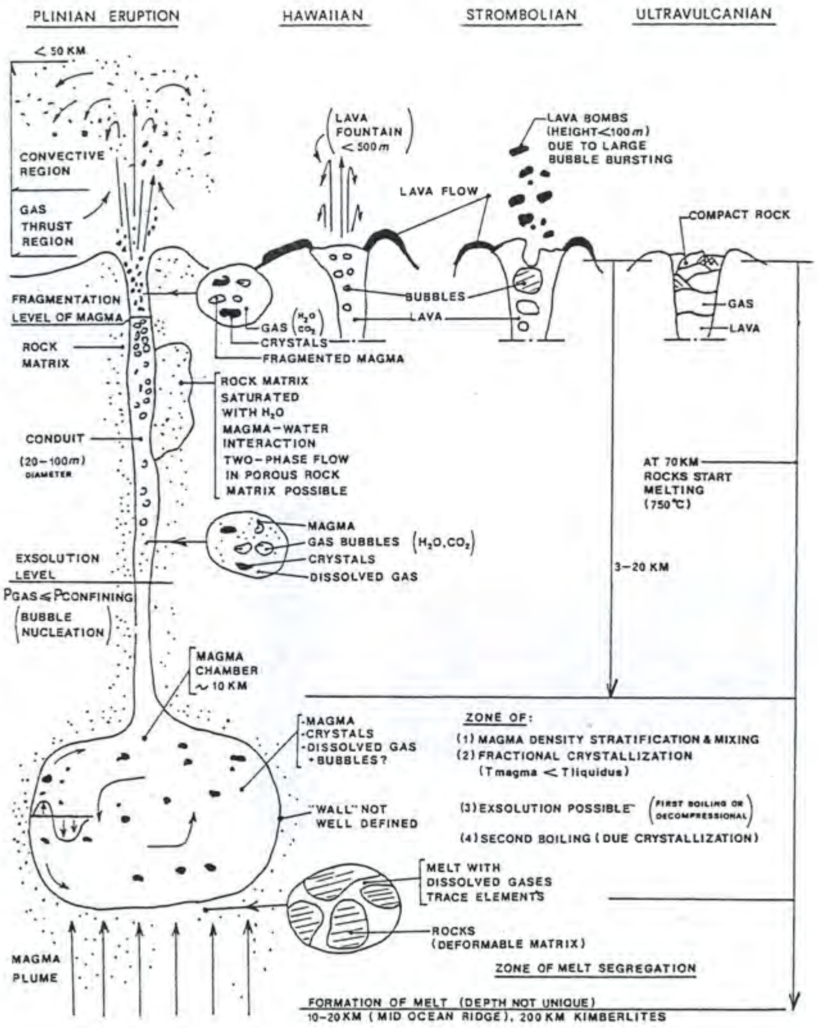

Figure 28. Schematic illustration of a volcanic system such as Vesuvius in the open conduit condition. The figure illustrates different domains of the volcanic complex which are coupled together (Dobran, 1991b).

The construction of a global volcanic simulator calls for an integration of domain models into an efficient computational algorithm. Due to the complexity and coupling of these models this is not an easy task and will require an efficient use of computational resources. The material in the following sections is organized into research needs required to model the thermofluid-dynamic and structural mechanics phenomena of the volcanic complex at Vesuvius. Following this, we discuss the required breakthroughs in mathematical and physical modeling sciences, and conclude with research needs aimed at implementing computer algorithms and computing systems. The research modeling requirements pertaining to lava flow are not discussed below, since they parallel those at Etna as described in section 3.3.2 and in the Appendix.

6.2 Thermofluid-Dynamic Research Needs

Dobran et al. (1990) reviewed an extensive body of literature pertaining to the modeling of volcanological processes in order to assess the possibility of developing a global volcanic simulator. They concluded that very important aspects of past volcanological modeling studies have been the identification of processes able to produce different types of volcanic eruptions, permitting the development of complex thermofluid-dynamic models involving multidimensional, multiphase, and multicomponent flows in the future (Dobran, 1991b). In this section, we will examine past thermofluid-dynamic research aimed at Vesuvius and identify the required research needs to develop realistic simulation capabilities of thermodynamic and fluid-dynamic phenomena in different parts of the volcanic system.

6.2.1 Melt Segregation Modeling of the Vesuvian Feeding System

Melt segregation deals with melting and melt extraction from rocks in the mantle and lithosphere leading eventually to the accumulation of melt in the magma chamber of Vesuvius. There are no melt segregation studies pertaining to the Vesuvian feeding system. This is a serious omission and future studies should be directed at constraining the conduit development and magma transport within the lithospheric mantle. The process of conduit evolution is significant since it may provide a mechanism for the introduction of large-scale chemical and isotopic heterogeneities into the lithospheric mantle. This can produce assimilation of wall rock and yield different hybrid compositional and isotopic trends as a conduit or conduits develop below the Vesuvian magma chamber. The temporal changes of the lithospheric contamination during magma ascent therefore need not reflect the geochemical and isotopic characteristics of its source region. As indicated in section 3.1.2, petrological, geochemical, and isotopic studies must be properly constrained by the thermodynamic and fluid dynamic phenomena taking place in the feeding system of Vesuvius. Some very important aspects of these studies are the determination of the geothermal gradient in the magma supply system and establishment of probabilities for dynamic perturbations leading to solitary wave transport, diapiric magma transport, or lithospheric fracture. Magma transport by lithospheric fracture may be very rapid and allow much smaller melt volumes than diapiric transport (Fowler, 1990b).

The previous thermofluid-dynamic modeling studies of melt segregation not pertaining to Vesuvius have dealt with melt extraction and one- and two-dimensional solutions of thermofluid-dynamic transport equations pertaining to combined melting and melt extraction with complete and limited (eutectic) solid solubility and trace element concentrations. The relevant works are those of Beere (1975), Bulau et al. (1979), Watson (1982), Jurewicz and Watson (1984,1985), Waff (1986), and Riley and Kohlstadt (1990) (melt migration); McKenzie (1984, 1985), Richter and McKenzie (1984), Ribe (1987), Fowler (1990a,b) (melt extraction and melting); Marsh (1982,1987), Morris (1982), Scott and Stevenson (1984), Richter and McKenzie (1984), Ansari and Morris (1985), Daly and Raefsky (1985), Barcilon and Richter (1986), Olson and Christensen (1986), Scott et al. (1986), Singer et al. (1989), Fowler (1990b), and Whitehead and Helfrich (1990) (magma waves and diapirs); Nicolas and Jackson (1982), Emerman et al. (1986), Nicolas (1986), Fowler (1990b) (magma transport by fractures). Proper melt segregation studies require appropriate boundary conditions to close the mass, momentum, and energy conservation equations. To date, these conditions have not been adequately discussed and have not been even addressed for Vesuvius. Dobran et al. (1990) and Fowler (1990a) provide further information on the current state of the art in physical modeling equations of melt segregation and discussion of constitutive and boundary conditions.

The melt segregation studies addressed to the understanding of the Vesuvian magma feeding system should include:

1. Re-examination of physical modeling equations of melt segregation as proposed by McKenzie (1984) and Fowler (1990a,b) for application to the Vesuvian magma feeding system. The results from thermodynamic, petrological, and isotopic studies suggested in section 3.1.2 will help to constrain the appropriate model of melt transport (see, for example, Ryan, 1990; Sato et al., 1989).
2. Studies of constitutive equations of melt and matrix stress tensors, melt permeability, and thermodynamic equilibrium constraints deduced from phase diagrams produced from studies discussed in section 3.1.2.
3. Boundary conditions studies. Melting is central to the dynamics, and the boundary conditions must properly reflect the kinematic, stress, and thermal conditions surrounding the lithospheric magma transport conduit(s).

4. Establishment of magma transport constraints. As discussed in section 2.3.3, it is hypothesized that magma supply to the magma chamber of Vesuvius is in batches. The petrological and isotopic results which point in this direction must, however, be constrained by the thermodynamic and fluid-dynamic constraints, and it remains to be established whether the latter constraints can produce melt transport by diapirs, propagating fractures, *etc.*
5. The understanding of melt transport at Vesuvius depends critically on an integrated approach, which includes thermodynamics, petrology, isotope geochemistry, thermofluid-dynamics, and geophysics.

6.2.2 Magma Chamber Modeling of Vesuvius

Studies of phenocrysts content of many lavas indicate that lavas with more than 55 vol% of phenocrysts are rare (Marsh, 1981), implying that magmas with larger crystal content than this amount are too viscous to be erupted. The critical crystal content of magmas decreases with magma viscosity and it is thus expected that magma chambers can only be concentrated in regions where the volume of melt exceeds about 60 vol%. This melt content can be taken as a *constraining condition* for the Vesuvian magma chamber when the conduit closed following the AD 79 eruption. Based on this assumption and measured phenocryst content ϕ_c of the erupted magma of Vesuvius in AD 79, it is possible to estimate the ratio of erupted volume of material V_e and magma chamber volume V_T, *i.e.*

$$\frac{V_e}{V_T} \approx 1 - \frac{0.6}{1-\phi_c} \approx 0.1 - 0.2 \qquad (1)$$

where use was made of $\phi_c \approx 0.2\text{-}0.3$ (Civetta et al., 1991). According to this result and 2 km^3 of erupted magma, the Vesuvian magma chamber after the AD 79 eruption had a volume from 20-40 km^3, or an equivalent spherical diameter from 3.5-4 km. In section 6.5, use will be made of the estimated magma chamber size to determine computer resources necessary for modeling magma chamber dynamics.

The high crystal contents of erupted magmas during the AD 79 and 1631 eruptions of Vesuvius (Civetta et al., 1991; Rosi et al., 1992) coupled with the above crystal limiting condition for magma eruptivity from the magma chamber implies that the plinian magma chambers of Vesuvius cannot be assumed as single phase reservoirs of liquid as in past magma chamber modeling (Spera et al., 1984, 1986; Nilson et al., 1985; Hansen and Yuen, 1987). The convection in the magma chamber of Vesuvius should account for compositional variations caused by fractional crystallization, partial melting and assimilation of the walls and roof of the chamber, mixing of magma from the feeding system with pre-existing material, and, possibly, volatile exsolution caused by compositional variation and/or pressure decrease in the chamber during the open-conduit condition. Some of these processes have been studied separately in the past for generic magma chambers and the reader is referred to Dobran et al. (1990) for a review; Huppert and Sparks (1984), Sparks and Huppert (1984), and Sparks et al. (1984) for convective fractionation or separation of liquid from crystals by compositional convection; Huppert et al. (1982), and Turner et al. (1983) for volatile effects on convection; Sparks et al. (1980), Huppert and Sparks (1984), Cambell and Turner (1985,1986), Turner (1985), and Huppert et al. (1986) for magma replenishment effects on convection; and Kerr and Tait (1985,1986) for convection in cumulus piles of crystals. The multiphase nature of the Vesuvian magma chamber material is also expected to have different magma withdrawal dynamics than established in previous studies (Spera, 1984; Spera et al., 1986; Blake and Ivey, 1986a,b).

The chemical compositions of Vesuvian magmas (Civetta et al., 1991; Rosi et al., 1992) indicate at least five crystallizing phases (K-feldspar, clinopyroxene, biotite, leucite, nepheline) which must be appropriately modeled by a thermofluid-dynamic model of magma chamber. The crystallization is not an instantaneous process; rather it is limited by the rate at which new crystals nucleate and grow (Kirkpatrick, 1976; Brandeis et al., 1984; Brandeis and Jaupart, 1986, 1987). These crystallization parameters depend in turn on the chamber geometry, efficiency of the convective process, and magma chamber boundary conditions (Valentine, 1992). Each crystallizing phase consists of several different sizes whereby each size can be regarded as a *population.* If exsolution of magmatic gas also takes place, there are additional bubble populations to be considered. With n crystal populations, m gas bubble populations, and one liquid or melt population there are n+m+1 populations or phases that may have to be considered in modeling the convection, crystallization, and gas exsolution processes in the magma chamber of Vesuvius. The melt component consists of k different species or components that also need to be appropriately modeled. In a superimposed multiphase continua modeling (Dobran, 1984, 1985, 1991a; Valentine, 1992), it is thus necessary to solve simultaneously n+m+k balance of mass equations, n+m+1 vector momentum equations, and n+m+1 energy equations. These partial differential equations are reasonably well understood, except for the constitutive equations which must model crystal kinetics (crystal nucleation and growth rates), gas exsolution, momentum and energy transfer between the phases, chemical and thermal diffusivities of melt components, and rheology of magma. Some of these constitutive equations are known reasonably well whereas others are not.

The magma chamber modeling approach outlined above must also account for the changing size of the chamber as new magma is injected or ejected from the chamber, or as the chamber walls melt or solidify. This can be accomplished automatically in the mass, momentum, and energy balance equations by assuming

that the stress tensors of different material populations can be mathematically modeled as viscoplastic or viscoelastic materials with ranges of applicability determined by the temperature, stress, and strain states of rocks and crystal and bubble populations. As discussed above, the magma chamber domain must be properly coupled with the soil or rocks domain, which may be accomplished by means of viscoelastic or viscoplastic subdomain depending on the modeling strategy of the latter domain (see section 6.3). The coupling of domains requires special attention and is further discussed below in section 6.5.

Some specific magma chamber modeling objectives should include:

1. Determination of the appropriate number of melt components, and crystal and bubble populations. It is important in this effort to establish a minimum number of populations which can simulate adequately the crystal fractionation and convective processes in the magma chamber. This information should come from the research efforts described in section 3.
2. Establishment of the appropriate forms of physical modeling equations for simulation of multicomponent, multiphase, and three-dimensional phenomena in the chamber. In this study it is important to assess possible simplifications of the mass, momentum, and energy balance transport equations resulting from kinematic, dynamic, and chemical similitude analysis.
3. Studies of constitutive equations of multicomponent and multiphase mixtures. This study should include linear, nonlinear, viscoelastic, and viscoplastic rheologies, crystallization kinetics, and chemical and thermal diffusion with cross-coupling effects. The constitutive equations should be studied using the modern principles of mechanics (Truesdell and Noll, 1965; Dobran, 1991a) to insure the satisfaction of proper invariance conditions of magma chamber materials. In this study, it is also important to consider the structural effects of multiphase mixtures (Dobran, 1991a, 1992b) which account for inertial, dilatational, and rotational effects.
4. Initial and boundary conditions studies which are constrained by geophysical, petrological, volcanological, thermodynamic, and other studies. Important parameters to be identified are: initial size, shape, and composition of various products in the magma chamber (the effect of rock and fluids (water) assimilation from the collapsed magma chamber or conduit wall environments following the conduit closure after the AD 79 eruption should be established). Magma chamber boundary conditions involve the kinematic (velocity), dynamic (stress), thermal (temperature and/or temperature gradient), and chemical (concentration and/or concentration gradient) conditions. These conditions must be specified for all times at the boundary of the magma chamber volume and should be established from the field studies suggested in sections 3.1.2 and 6.3.

5. Incorporation of physical data and thermodynamic phase diagrams of melting and crystallization of multicomponent magma at Vesuvius into equations suitable for manipulation by a computer.

6.2.3 Conduit Domain Modeling

The conduit domain can be characterized by propagating fractures induced by magma and conduits where the magma may exsolve the dissolved gases, fragment into pyroclasts, and interact with conduit walls and surrounding aquifers. The conduit domain modeling strategies may involve an initial opening phase whereby magma propagates through one or more fractures toward the surface of the Earth, an open-conduit magma flow phase, and a closing conduit phase during the vaning of the eruption.

Only few modeling efforts have dealt with magma flow modeling in volcanic conduits of Vesuvius, or more specifically to the AD 79 eruption. These studies involve steady-state, one-dimensional, nonequilibrium, and two-phase flow (Dobran, 1992a; Papale and Dobran, 1992a), and transient, one-dimensional, isothermal, and homogeneous two-phase flow (Ramos and Dobran, 1993) modeling of magma and gas. In these models, account is taken of the conduit wall stratigraphy (Balducci et al., 1985), magma composition (Barberi et al., 1981), crystal content (Civetta et al., 1991), eruption dynamics reconstructed from stratigraphic and historic records (Lirer et al., 1973; Sheridan et al., 1981; Sigurdsson et al., 1982, 1985, 1990; Carey and Sigurdsson, 1987; Cornell and Sigurdsson, 1987), and magma density, viscosity, and gas exsolution determined from magma composition, pressure, and temperature. An important conclusion from the modeling of Dobran (1992a) and Papale and Dobran (1992a) is that the magma composition of Vesuvius during the AD 79 eruption produced a large viscosity and may have had a large influence on the magma pressure distribution along the conduit and on the eruption dynamics, as it occurred in the 1980 Mt. St. Helens eruption (Papale and Dobran, 1992b). The above two-phase flow modeling of magma ascent in volcanic conduits may be contrasted with previous modeling efforts of Wilson et al. (1980), Wilson and Head (1981), Vergniolle and Jaupart (1986), Buresti and Casarosa (1989), and Giberti and Wilson (1990), where the pressure distribution along the conduit was assumed *a priori*, or where the effect of magma composition on physical and rheological properties of magma and two-phase flow before magma fragmentation was ignored. As concluded by Papale and Dobran (1992b), the composition, and, therefore, the viscosity of magma is a fundamental quantity in determining the magma flow characteristics and cannot be ignored in modeling magma ascent in a volcanic conduit. The transient two-phase flow modeling of magma ascent during the AD 79 eruption of Vesuvius (Ramos and Dobran, 1993) demonstrates very rapid magma ascent times (several seconds) if left to propagate from a depth along an open conduit.

During the conduit opening phase, the buoyant magma ascends toward the surface through one or more propagating fractures (Spence and Turcotte, 1985, 1990; Spence et al., 1987; Lister and Kerr, 1991). For a fracture to propagate, the buoyancy force on the magma must exceed the retarding viscous force due to magma flow, the elastic, viscoelastic or viscoplastic force necessary to keep the fracture open, and the tectonic compressive forces. During fracture propagation, thermal effects can have a significant influence on this propagation which to date has not been quantifed. The crack propagation due to the ascending magma leading to a conduit opening is currently being investigated as one of the objectives of the Etna Laboratory Volcano Project (see Appendix). In this study the fluid-dynamic, acoustic, and thermal effects will be considered in determining the formation of a conduit at Etna. For Vesuvius, the following modeling objectives should be pursued:

1. Studies directed at establishing crack propagation due to hydrodynamic, thermal, and acoustic effects in viscoelastic and viscoplastic media. For this purpose, multidimensional hydrodynamic modeling equations and linear and nonlinear constitutive equations of rocks will have to be considered.

2. Crack formation can also occur in the presence of temperature gradients caused by the intruding magma. This causes thermal elongations and stresses which may exceed the failure stress of rocks. The temperature-induced crack propagation is intimately coupled with hydrodynamic, thermal, and acoustic effects, for as a crack opens the magma may flow into the crack.

3. The overall modeling objective of crack propagation studies should be the development of a model capable of accounting for the formation of fracture or fractures which produce an open-conduit magma flow.

The flow of magma in an open-conduit of Vesuvius can produce exsolution of the dissolved magmatic gas, magma fragmentation, and magma-water interaction (Sigurdsson et al., 1990; Bertagnini et al., 1991; Dobran, 1992a; Papale and Dobran, 1992a; Rosi et al., 1992). The high viscosity magmas of Vesuvius can produce large differences between the lithostatic and magmatic pressures along the conduit. These pressure differences can cause conduit wall rupture or erosion (Macedonio et al., 1992) and water pouring into the conduit from underground aquifers (Dobran and Papale, 1992a). The inward and outward wall collapses during the AD 79 eruption of Vesuvius inferred from the steady-state modeling of magma ascent are in accord with the shallow and deep lithics found in the deposits of the AD 79 eruption (Barberi et al., 1988). The steady-state model of Dobran (1992a) and Papale and Dobran (1992a) cannot model the transient processes associated with conduit wall erosion and it assumes an equilibrium gas exsolution law. The latter assumption may be in error when applied to the transient analyses of gas-magma transport. Transient analyses of magma transport in

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1. Transient modeling of the magma-gas flow, erosion, and magma-water interaction. A one-dimensional flow assumption in this modeling will need to be justified at the conduit exit where vent flaring may produce significant multidimensional effects (Kieffer and Sturtevant, 1984). A proper transient, two-phase flow model of magma ascent in the volcanic conduit at Vesuvius must allow for the conduit geometry change produced by erosion, mass transfer from/to the wall, and volcanic tremor (wall vibrations).

2. Wall erosion modeling. Macedonio et al. (1992) identified several mechanism which may produce erosion in volcanic conduits: (a) wall shear stress due to the flowing magma below the magma fragmentation level and due to the gas-particle mixture above this level; (b) particle collisions with the wall above the magma fragmentation level; (c) inward and outward wall collapses caused by the difference between the lithostatic and magmatic pressures; and (d) volcanic tremor. These erosion processes may produce very dense two-phase mixtures near the magma conduit, which, in turn, are carried along by the fluid motion affecting the pressure drop. How these eroded products are, in turn, eroded by the shear of the surrounding fluids and how they affect the velocity and pressure fields should be determined by developing models which account for these effects. These models should be incorporated within the constitutive equations of the mixture. The results from volcanological studies identified in section 3 can be used to establish the constraints on the above erosion mechanism and identify the proper constitutive equations for use in erosion modeling.

3. During a magma-water interaction process it is necessary to establish the conditions for water inflow into a volcanic conduit. This may be accomplished by producing simple physical models of water flow in porous and fractured soils and rocks which also account for the fractured wall near the conduit and for the difference between the lithostatic and magmatic pressures. Dobran and Papale (1992a) modeled water pouring into the volcanic conduit of Vesuvius during the AD 79 eruption and found very rapid pressure rise times in the conduit if water interacts with fragmented magma. This interaction may terminate the water inflow and destroy the volcanic edifice. Modeling of water inflow into a conduit of Vesuvius should be developed on the basis of the geological and geophysical data discussed in sections 3 and 4.

4. Modeling of the magma fragmentation process is long overdue. Magma fragments when it has a difficulty of flowing between the dispersed gas phase. For "normal" liquids, the fragmentation or change of flow regime occurs at a gas volumetric fraction from 0.7-0.8 (Wallis, 1969), which is generally assumed to be valid for magmas based on pumice studies (Sparks, 1978). The validity of this empirical relation should be established from modeling of the dynamics of flow regime change and external parameters which may produce such a change. For example, water inflow into a conduit may produce stress and shock waves that may fragment magma at low gas volumetric fractions (Sheridan and Wohletz, 1983; Wohletz, 1986; Dobran et al., 1990; Zimanowski et al., 1991). Studies from the field should be used to construct the appropriate constitutive equations for magma-water interaction.

5. Bubble dynamics modeling in magmas should be directed at establishing the proper constitutive equations for magma-gas viscosity and bubble growth in the presence of other bubbles in a decompressing environment. The previous studies of Rosner and Epstein (1972) and Sparks (1978) should be used as starting points in bubble dynamics modeling.

6. The fragmentation of pyroclasts above the magma fragmentation level in a conduit can produce a spectrum of particle sizes which can subsequently affect the volcanic column dynamics (Dobran et al., 1992). Such a fragmentation modeling study is very important in order to establish the mechanisms of fine-scale fragmentation of pyroclasts. The shearing action by the high-speed gas flow can cause a boundary layer to be formed on the surface of a particle which can be subsequently stripped away and lead to particle breakup. Constitutive equations are needed to model this and other possible fragmentation processes of pyroclasts after the magma is fragmented. Field data can be employed to establish other particle breakup mechanisms and constrain the forms of constitutive equations.

7. Studies directed at magma ascent in *real* conduits of Vesuvius need to be performed in order to simulate the magma ascent correctly. For this purpose, it is necessary to establish the constraints on conduit geometries from field data (geology and geophysics), as indicated in sections 3 and 4.

The closing conduit phase of an eruption may occur due to pressure decrease in the magma chamber. This pressure decrease can produce chamber and conduit wall collapses which may totally obstruct magma ascent or change the condition for magma eruptivity (Marsh, 1981) by producing a large fraction of solid phase in the chamber. This scenario, which produces a caldera, is more likely to occur after the termination of a plinian or subplinian eruption phase and may not completely seal the conduit due to the stopping effect of magma as discussed above. The stopping effect may subsequently produce strombolian and lava effusion activities until magma and water supplies from shallow regions of the volcano are exhausted. The collapsing walls introduce considerable complexity in modeling this very important phase of eruption and several modeling approaches should be pursued to understand the physics and to develop a useful model of the conduit closure phase for use in the volcano simulator. As the stress (or pressure) and temperature of the surrounding wall materials vary during the closing conduit phase, these materials may pass through various patterns of behavior, wherein different deformation mechanisms dominate at each step. Thus we should expect a viscous behavior of liquid magma, and elastic, viscoelastic, and viscoplastic behavior of rocks, depending on their thermodynamic and mechanical states. Some possible approaches to this modeling are:

1. Production of *deformation maps* for the materials surrounding the eruption center. This study, which is also useful for magma chamber modeling, should identify different materials near the center of the volcanic complex and establish their rheological behavior as a function of pressure, temperature, fluid content in pores, *etc.* For this purpose, experimental studies are needed to identify the stress and heat transfer constitutive equations of the different rock types that constitute the Vesuvian volcanic complex.
2. Development of a multiphase thermofluid-dynamic model which accounts for the magma and the surrounding conduit wall materials including the aquifers. This multiphase model would consist of several representative materials from Vesuvius where each phase would be described by generalized constitutive equations. For example, the stress tensor of a phase can be modeled as a linear or nonlinear viscoelastic or viscoplastic material with temperature dependence. The deformation maps would then be used to determine the regions of applicability of different constitutive assumptions. A model of the closing conduit phase should be able to reproduce the closing of the 1631 eruption of Vesuvius where the caldera and conduit walls collapsed and part of the cone was decapitated due to the emptying of the aquifers.

Modeling of the conduit domain may be as complex as modeling of the magma chamber domain, both of which must be appropriately coupled in a subdomain (section 6.5). In this manner each domain evolves depending on the boundary conditions of the other domain, and both domains contribute toward the evolution

of the volcanic complex. The complete evolution of the volcanic system also depends on the coupling between the magma chamber and conduit domains with the soil or rocks and pyroclasts domain models as discussed below.

6.2.4 Pyroclasts Domain Modeling

The plinian and subplinian eruptions of Vesuvius have produced large-scale catastrophic effects in the Vesuvian area. They generated plinian columns, pyroclastic flows, and lahars. Figures 8-11 illustrate the tephra dispersal directions and plinian and pyroclastic flow deposit thicknesses. The reconstruction of tephra fall deposits (thickness, grain size, sorting, maximum-size distribution of pumice and lithic fragments) provides information about eruption dynamics, including column height, mass-discharge rate, and wind patterns (Carey and Sparks, 1986). This information can then be used for the construction of hazard-zonation maps, if it is assumed that future eruptions of Vesuvius will behave similarly as in the past. As seen in Figs. 8-11, it is clear that different plinian and subplinian eruptions of Vesuvius produced different effects in different regions surrounding the volcano and that physical models of tephra dispersal should be able to simulate the plinian and pyroclastic fall and surge distributions in these regions, depending on the eruption dynamics, wind patterns, *etc.* For these reasons, the simulations of tephra falls should be carried out in three dimensions with a radial extent of about 100 km and a vertical extent of about 30 km (perhaps even higher).

Tephra consist of fragments of rocks and lava that are ejected into the atmosphere and fall back to the Earth's surface. The degree of rock fragmentation or sorting and gas content exsolved from magma or released from hydrothermal systems during magma-water interaction, determine the tephra dispersal characteristics. Moisture increases the cohesiveness of tephra, and the condensation of water vapor in a volcanic column affects the evolution of the column. Due to the high temperature of the erupting gas-pyroclasts mixture, tephra falls can produce fires, cause welding of deposits, and change the rainfall/runoff relationships (Scott, 1989). Pyroclastic flows form from high-concentration dispersions of solids and gas that typically follow topographically low areas (Figs. 8-11). Pyroclastic-surge deposits form from low-concentration dispersions that are inflated and are, therefore, less topographically controlled than pyroclastic flows. Lahars are rapidly moving mixtures of rock debris mobilized by water, that originate on the slopes of the volcano or its surroundings. In contrast to the pyroclastic flows and surges which can affect areas high above valley floors and far from the vent, lahars are restricted to within tens of meters of valley floors. The discharge and, therefore, the width and depth of a lahar can change rapidly along its course depending on the mode of origin, grain size, sediment-water ratio, channel dimensions, *etc.* (Scott, 1989). During the 1631 eruption of Vesuvius, lahars were generated along the valleys of the cone of Vesuvius and Monte Somma (Rosi et al., 1992), indicating that water was produced from condensation of steam in the immediate vicinity of the vent and far from the vent from the erupting column.

The thickness of tephra falls during the AD 79 plinian eruption of Vesuvius was numerically modeled by Macedonio et al. (1988) by a tephra diffusion model (conservation of mass for tephra). The input to the model included wind data, eruption rate and duration, column height distribution with time, grain size distribution and settling velocities of tephra, and various coefficients. The three-dimensional solutions of the model predicted the erupted tephra distribution surrounding the volcano. The uncertainties related to the selection of inputs, assumption of particle diffusion taking place in the gas itself (valid only for particles of several microns or less), and omission of momentum and energy transport equations in modeling the development and radial spreading of the erupting cloud seriously limit this modeling strategy in its usefulness to *predict* tephra falls at Vesuvius during future eruptions. Since the model can only predict the thickness of tephra-falls of past eruption at Vesuvius, for which the deposit thicknesses are already known (Principe et al., 1987), it has a limited usefulness in serving as a basis for hazard-zonation mapping for the Vesuvian area. (In GNV (1992), the results from the model are used for delineating the hazard zones due to a plinian eruption, depending on the ground distribution of tephra.)

Physical modeling of volcanic columns requires the use of mass, momentum, and energy transport equations of multiphase flow for gas and particles (pyroclasts), and multicomponent flows for air and volcanic gases (Wohletz et al., 1984; Valentine and Wohletz, 1989a; Wohletz and Valentine, 1990; Dobran et al., 1992; Giordano and Dobran, 1993; Neri and Dobran, 1993). This modeling demonstrates the transient behavior of gas and pyroclasts above the vent even if the discharge from the vent is steady, oscillations of fountains of the collapsed columns and of the associated radially spreading pyroclastic flows, recirculation of pyroclastic flow material into the base of the column, generation of co-ignimbritic or phoenix columns above the pyroclastic flows, maintenance of the suspended (in the air) pyroclastic flow, condensation of water vapor after few minutes of the eruption, and different rates of pyroclasts sedimentation depending on the vent conditions and topographic features of a volcano. Figures 29-31 illustrate some of the characteristic features of volcanic columns using the above complex modeling approach. Figure 29 shows the development of a phoenix column above a pyroclastic flow, whereas Fig. 30 shows the gas temperature distribution in the atmosphere caused by a collapsing column. The effect of topography on pyroclasts distribution of a volcano is illustrated in Fig. 31. The cover page of this report shows a pyroclastic flow generated by the collapse of a column at Vesuvius similar to that which may have produced pyroclastic flows following the plinian gray eruption phase in AD 79. This flow reaches the Tyrrhenian Sea after about 200 s, which leaves very little room for people to escape alive from the nearby towns. The results from complex computer simulations are in accord with laboratory experiments (Carey et al., 1988), field observations of volcanic columns (Hoblitt, 1986), simple modeling approaches (Sparks and Wilson, 1976; Sparks et al., 1978), and point to a need for using these models for accurate determination of volcanic hazard (Dobran et al., 1992).

The numerical simulations of volcanic columns carried out to date with complex models have limited usefulness when attempting to simulate *real* volcanic columns. These simulations are two-dimensional, neglect condensation processes and are monodispersed (single particle size), model turbulence in a very primitive manner, and require very large computer simulation times in comparison with the duration of the eruption. The combined modeling of plinian columns and pyroclastic flows is particularly difficult with present models, since this modeling requires high resolution in many parts of the flow (pyroclastic flow and flow near the vent) and large spatial extents to establish the transport of tephra in the atmosphere.

Modeling of lahars is handicapped by the limited understanding of the physical processes of debris flows (Iverson and Denlinger, 1987; Mizuyama et al., 1987). Lahars are multiphase flows of different size particles or grains where sediment concentration may range from 40-80 wt% (Beverage and Culbertson, 1964). A lahar transforms into a hyperconcentrated flow as sediment is lost (a lahar-runout flow) and may possess different deposition characteristics than a pyroclastic flow. Current practical models of lahars employ one-dimensional forms of mass and momentum equations (Cheng, 1987; Barberi et al., 1992; Macedonio and Pareschi, 1992), where the flow is assumed to be homogeneous. Both these assumptions are generally not justifiable. In particular, the homogeneous flow assumption is valid in lahar-runout flows where the water-transported particles are very small, but not in debris flows where large-size blocks can have considerably different velocities than the transporting fluid. The one-dimensional flow assumption breaks down along narrow valleys. A proper lahar modeling at Vesuvius is especially difficult since it requires knowledge of water availability and changes of topographic features due to depositing tephra during an eruption. For this reason, lahar modeling should be integrated within the tephra model which can in turn model the water vapor condensation process.

The modeling of pyroclasts distribution in the atmosphere and along the slopes of Vesuvius should be accomplished by a complex multiphase and multicomponent physical flow model. Such a modeling is necessary to account for air and water vapor mixing, water vapor condensation, and gas-particle and particle-particle interactions. A volcanic column is characterized by a very large spectrum of particle sizes. The plinian eruption columns exhibit particle sizes from few microns to several centimeters with about 90 wt% of solids exhibiting a particle size less than 5 cm and 40 wt% less than 600 μm (Sparks and Wilson, 1976). The

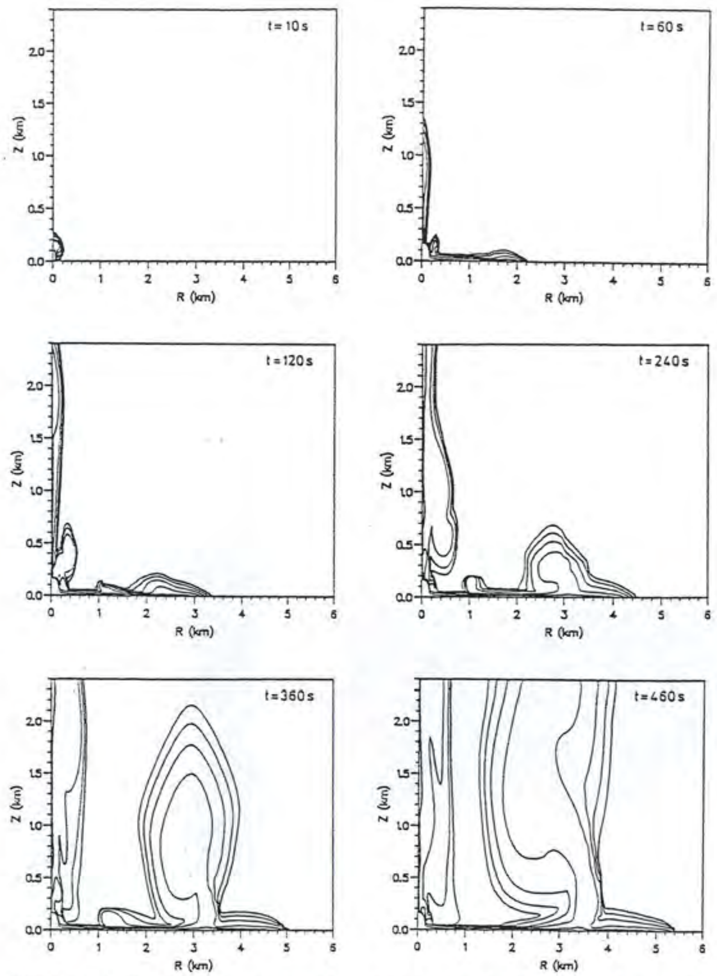

Figure 29. Distribution of water vapor volumetric fraction in the atmosphere at 10, 60, 120, 240, 360, and 460 s after an eruption with vent diameter of 100 m, temperature 1120 K, velocity 56 m/s, pressure 0.1 MPa, particle volumetric fraction 0.0754, and water vapor as the only gas phase at the vent. The contour levels shown are the exponents to the base 10 and, beginning from the outer or distant from the vent region, correspond to -10, -8, -6, -4, -2, -1, 0. Characteristic features of this eruption are the column collapse and formation of a fountain at about 10 s, and the development of a phoenix cloud above the pyroclastic flow after about 2 minutes (Dobran et al., 1992).

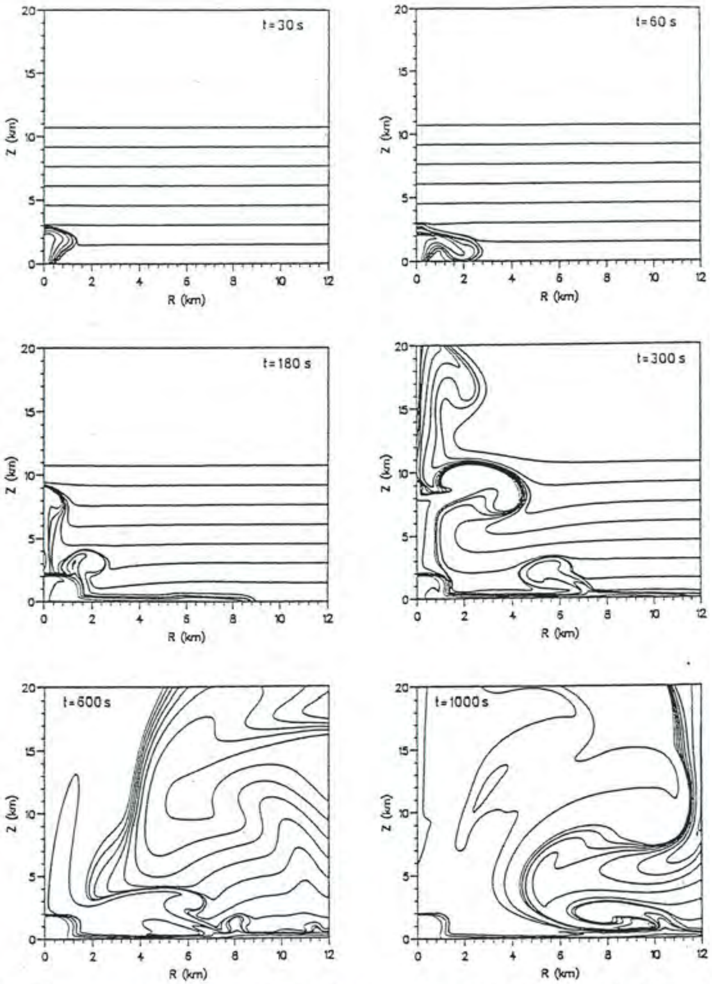

Figure 30. Gas temperature distribution in the atmosphere at 30, 60, 180, 300, 600, and 1000 s after an eruption with vent diameter of 600 m, temperature 1200 K, velocity 200 m/s, pressure 0.1 MPa, particle volumetric fraction 0.01, and water vapor as the only gas phase at the vent. A contour level in the figure represents the difference between the local gas temperature and the undisturbed atmospheric air temperature at the vent elevation. The temperature contours, starting from the inner or near the vent region, correspond to 900, 800, 500, 200, 0, -10, -20, -30, -40, -50, -60, and -70 K. The column forms a fountain at about 1700 m and a phoenix cloud which subsequently merges into a very large and hot volcanic plume (Dobran et al., 1992).

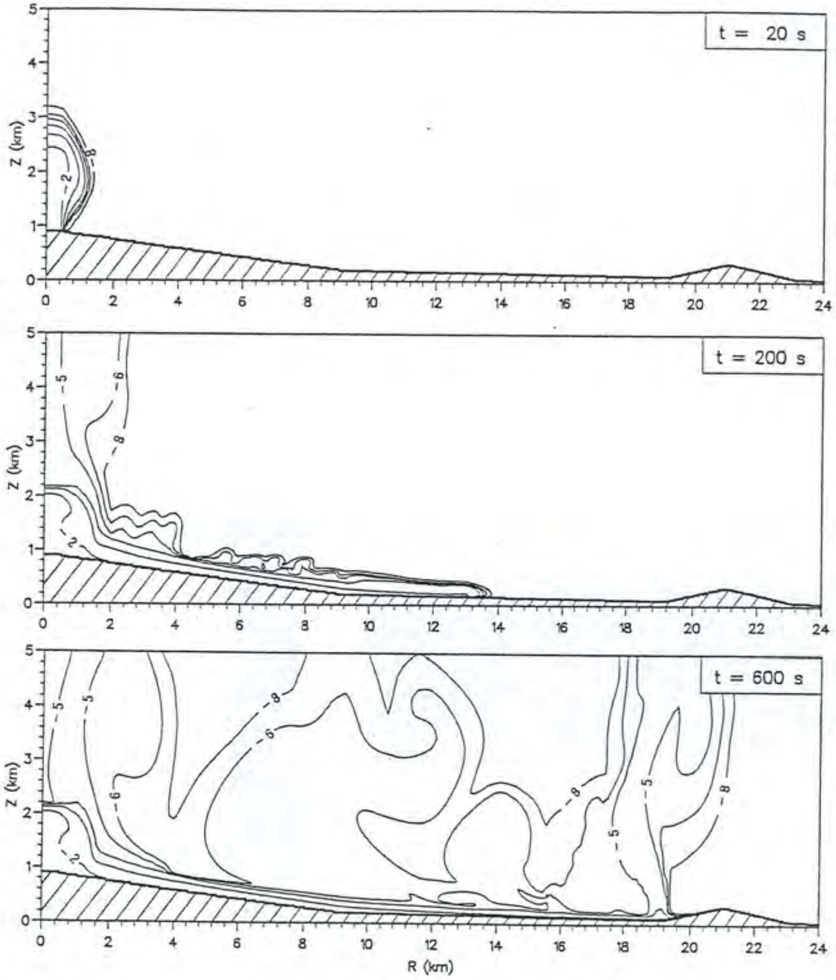

Figure 31. Development of a fountain, pyroclastic flow, and phoenix clouds above the pyroclastic flow of the IInd pyroclastic flow unit of Tuscolano Artemisio, Colli Albani (Latium, Italy). The vent diameter is 900 m, temperature 1373 K, velocity 150 m/s, pressure 0.1 MPa, particle volumetric fraction 0.015, and water vapor as the only gas phase at the vent. The particle volumetric fraction contours shown in the figure are exponents to the base 10 (Giordano and Dobran, 1993).

ultraplinian and large intensity plinian events produce 85 % of the total ejecta which are sub-millimeter in size, with 60 % being fine ash or material fines less than 63 μm (Walker, 1981). The ignimbrites also consist predominantly of sub-millimeter particles with a fine ash content from 15-85 wt% (Walker, 1981). The phreatomagmatic eruptions have even larger contents of fine ash than plinian and ultraplinian eruptions, whereas the strombolian eruptions tend to be poorly fragmented with about 95 wt% of particle sizes which are above 1 mm (Self et al., 1974; Walker, 1973, 1985). The size of tephra or particles determines the degree of nonequilibrium between gas and solid phases, and the larger this size is the larger will be the nonequilibrium (Dobran et al., 1992). For very low volumetric fractions of solids or pyroclasts in gas ($\alpha_p \leq 10^{-6}$), the particles have a negligible effect in modifying the gas turbulence structure, and the interaction between particles and turbulence is "one-way coupling". The particle dispersion in this case depends on the state of turbulence of the gas phase. For $10^{-6} < \alpha_p \leq 10^{-3}$, the volumetric particle loading is large enough to alter the turbulence structure, and a "two-way coupling" between gas and particles exists. Smaller diameter particles with larger surface area increase the dissipation of gas turbulence, whereas larger diameter particles produce vortex shedding and contribute to gas turbulence production. For $\alpha_p > 10^{-3}$, the interaction is a "four-way coupling" where there is a two-way coupling between gas and pyroclasts and between pyroclasts due to collisions.

The particle volumetric fractions in typical volcanic eruptions such as those at Vesuvius may range from about 0.01 at the vent to 0.6 or higher in the pyroclastic flow, and as low as 10^{-6} or less in the plinian cloud (Dobran et al., 1992). The wide ranges of particle sizes and volumetric fractions in volcanic columns present formidable modeling difficulties which can be conquered with well-defined research objectives. In order to achieve these objectives, the research needs aimed at developing a *real* modeling capability of pyroclasts distribution above the vent of Vesuvius and along its slopes should include:

1. Development of a transient, two-component, multiphase flow model involving mass, momentum, and energy balance equations in three dimensions. The two components in this model should be air and water vapor which together constitute a gas phase. Tephra should be divided into n granulometric classes or populations whereby each population represents a phase. The water condensed from water vapor should be divided into m water droplet populations. In this manner, the gas and n+m tephra and water droplet populations represent n+m+1 phases. This modeling then requires n+m+2 mass balance equations, n+m+1 energy balance equations, and 3(n+m+1) momentum balances. This equation set is of course not complete since we also require modeling of interactions between gas and different tephra and water droplet populations, which in general requires additional transport

equations (Dobran, 1991a, 1992b).

2. The above pyroclasts domain modeling should be split into three subdomains: (1) *dilute gas domain* which consists of dilute particulate suspension in the gas phase ($\alpha_p < 10^{-3}$), such as a volcanic cloud sufficiently above the vent of pyroclastic flows, (2) *dense gas domain* which consists of dense particulate suspensions in the gas phase, such as the jet thrusting region, fountain, and pyroclastic flows and surges, and (3) *dense liquid domain* which consists of dilute or dense particulate suspensions in liquid (water), such as debris and lahar-runout flows. The appropriate coupling between the subdomains is discussed in section 6.5.
3. The modeling of gas-particle dispersions in the dilute gas domain should involve an Eulerian approach for the gas and fine dust, and Lagrangian approach for large-size tephra and water droplet populations. The former approach treats the gas and fine dust as interpenetrating continua, whereas the latter approach treats particle populations as discrete particles in the flow (see Crowe, 1982, for an example). The effect of interphase momentum and energy transfer between gas and particle populations can be accounted by the appropriate source terms in the gas and particle transport equations. A typical solution approach involves: solving for the gas flow without particle populations, calculating particle trajectories and source terms using the gas flow field solution from the previous step, recalculating the gas flow field with source terms, and repeating the procedure until convergence is achieved. An advantage of this modeling is the absence of numerical diffusion in particle field computations and economy of computations over large extents (three-dimensional dispersion of a plinian column).
4. Turbulence modeling strategies in the dilute gas domain must be evaluated with caution before implementing them in a turbulence model of the atmosphere. Normally, the atmosphere is not very stable, and a disturbing hot volcanic plume can render it unstable and produce significant perturbations and turbulence. Whether the gas phase turbulence in volcanic columns should be modeled by simple eddy-diffusivity and subgrid scale turbulence models (Wohletz et al., 1984; Dobran et al., 1992), or with more complex turbulent kinetic energy and dissipation rate models (Adeniji-Fashola and Chen, 1990; Dobran, 1990), or with still more complex Reynolds stress models (Dobran, 1990), requires a careful consideration of alternatives, modeling accuracy, and efficiency of implementation. A two-way coupling between the gas and particulate phases can be introduced by a stochastic Lagrangian approach (Mostafa and Mongia, 1988).
5. Modeling of gas and pyroclasts populations in the dense gas domain should involve an Eulerian approach whereby *all* the phases are treated as interpenetrating continua. Dense multiphase flows include four-way coupling between gas and particle populations, and presently known turbulence theories become inadequate to model real physical processes. Suitable approaches in modeling dense suspensions involve the use of results from structured theories of multiphase mixtures (Dobran, 1991a) or from kinetic theory (Chapman and Cowling, 1970; Jenkins and Savage, 1983; Lun et al., 1984; Savage, 1988). The latter theory was used by Dobran et al. (1992) and Giordano and Dobran (1993) to produce the results in Figs. 29-31. There are several options for modeling dense multiphase flows, neither of which is in a state of complete maturity. For this reason, a great deal of care must be involved in selecting the proper modeling approach for dense particulate suspensions.
6. Modeling of dense and dilute particulate suspensions in liquids (debris and lahar-runout flows, respectively) should involve an Eulerian approach. The particle-particle interaction in these flows is much less pronounced than in dense gas-particle flows and the current two-phase flow kinetic theory approach cannot be used; the results from structured theories of multiphase mixtures should be used instead.
7. Constitutive equations. Proper closure of the mass, momentum, energy, and other transport equations (turbulent kinetic energy, dissipation rate equation, Reynolds stress equations, equilibrated inertia and equilibrated moments equations, kinetic transport equations, *etc.*) requires appropriate constitutive equations for mass, momentum, energy, inertia, and other variables. As such, the development of these equations should be based on the modern principles of mechanics (Truesdell and Noll, 1965; Dobran, 1991a) and careful evaluation of pertinent experimental data.

From the above it should be clear that a proper modeling of tephra dispersal in the atmosphere and along the slopes of Vesuvius will involve significant efforts to develop useful and reliable model(s). At present very complex phenomena of volcanic columns are being modeled, but they are modeled neither efficiently nor, probably, very accurately. To develop an efficient modeling of volcanic columns requires the development of complex models to understand the physics and less complex ones which can reproduce this physics reasonably well in a computationally effective manner. In section 6.5 some of these issues are discussed further.

6.3 Structural Mechanics Research Needs

The geological research objectives described in section 3.1.2 call for the definition of volcanic edifice conditions. This requires the establishment of a *geologic model* of Vesuvius, such as radial, lateral and cone structures, dykes or eruptive fissures, and the densities, porosities, and permeabilities of each of the heterogeneous parts of the Vesuvian system up to and beyond the magma chamber depth. The identification of temperatures and tectonic stresses in different regions of the system also forms part of the geologic model of Vesuvius. A proper construction of the geologic model of Vesuvius is a prerequisite for setting up an adequate structural model of the volcano.

The rocks surrounding the magma chamber and volcanic conduit can behave in brittle or ductile manner depending on pressure, temperature, and fluid pore characteristics. Due to previous intrusions and eruptions, the rocks near the magma chamber and surrounding the conduit are probably very fractured, except for the rocks in the immediate vicinity of the chamber and open conduit. In these regions the temperature approaches the magma temperature and rocks will behave viscoelastically or viscoplastically, depending on the rates of deformation and applied stress levels. Further away from the high temperature regions, the rocks will deform elastically on a short-time scale and viscoelastically on a long-time scale (Price and Cosgrove, 1990). The pressure of fluids (water) in rocks reduces the strength of rocks, and those rocks saturated with fluids will tend to behave in a brittle manner. High-fractured regions of the volcanic complex will also behave like low strength brittle materials. Furthermore, when the rocks behave viscoelastically, they tend to behave as *nonlinear viscoelastic materials* (Heard, 1963; Rutter, 1974). At Vesuvius, we should expect highly heterogenous subsurface regions (Fig. 18), whereby the heterogeneity is caused by the nature of rocks (lavas, pyroclastites, sedimentary rocks, thermometamorphic rocks) and different temperature distributions.

Before setting up a rock model it is important to establish *deformation maps* discussed in section 6.2.3. These maps would indicate whether at a given temperature and stress the specific rock types should be treated as linear or nonlinear elastic, viscoelastic, or viscoplastic materials. Such maps have never been produced for any volcano, but are indispensable for realistic mechanical modeling of a volcano. In the structural modeling of the Phlegraean Fields volcanic complex, Bianchi et al. (1984) used temperature-dependent elastic parameters of the medium which becomes cooler from the chamber to the surface. In a related work, Bianchi et al. (1987) refined their previous model by also considering the effect of temperature and medium heterogeneity (tuff, lava, fractured rock) but employed average elasticity parameters. Ryan et al. (1983) in their study of magma withdrawal from a sill-like storage compartment treated the volcanic pile as an anisotropic medium where elastic properties are different in the vertical and horizontal directions. Chevallier and Verwoerd (1988, 1990) structurally modeled an oceanic interplate basaltic volcano based on a heterogeneous geological model and isothermal and nonisothermal temperature fields. They employed an elastic rock analysis and accounted for temperature-dependent elastic parameters, showing that a temperature heterogeneity in the model produces a better geological system constraint. The mechanical and thermal modeling of Chevallier and Verwoerd suffers from the assumption of uniform far-field stresses which may not be justifiable as discussed by Sartoris et al. (1990). These latter authors carried out an elastic analysis of the Phlegraean Fields volcanic complex which included different stresses produced by the magma in the magma chamber, at the surface of the Earth, and at large horizontal distances from the chamber. The host medium in this work was assumed to be homogeneous, isotropic, linearly elastic, and isothermal. The surrounding magma chamber rocks were assumed to be fractured with a tensile strength of 10 MPa, and no account for frictional failure of rocks below the Phlegraean Fields caldera was taken in the model. Sartoris et al. (1990) concluded that the magma chamber stability is mainly dependent on the gravitational force and external boundary conditions. Chery et al. (1991) studied the problem of long-term ground deformation caused by the magma emplacement into the crust. Their mechanical model is based on thermally coupled elasto-visco-plastic rheology and finite deformations, and was solved by means of a finite elements method. They showed that the crustal deformation depends on the relative importance of different rheologies in the crust. Paul et al. (1987) divided the volcanic edifice of Mt. St. Helens into an assemblage of blocks in order to model highly heterogeneous and discontinuous mechanical behavior of the edifice. The block deformations were studied by increasing the internal pressure within the volcano (simulating magma intrusion) and horizontal acceleration (simulating an earthquake). Paul et al. (1987) established that the deformation and failure patterns are dependent on the coefficient of friction at block boundaries. Figure 32 illustrates a cross-section of Mt. St. Helens just before the May 18, 1980 eruption, and the modeled deformations of the volcano for a magma chamber pressure of 86 MPa.

From the above, it is evident that highly complex volcanic structures can be modeled provided that geological models of volcanoes can be constructed. The best known geological model of Vesuvius shown in Fig. 18 is very incomplete and speculative, and deformation maps are nonexistent. The structural mechanics research needs aimed at Vesuvius should include:

1. Establishment of *deformation maps* based on a geological model of Vesuvius. These maps should include regions surrounding the magma chamber and conduit, in both closed- and open-conduit conditions. The information available in the literature on elastic, viscoelastic, and viscoplastic rocks must be carefully evaluated before being used for the development of deformation maps.
2. Structural stability of the cone. An analysis similar to that of Paul et al. (1987), but applied to Somma-Vesuvius, should provide valuable information regarding the stability of the cone. The southern part of this cone appears

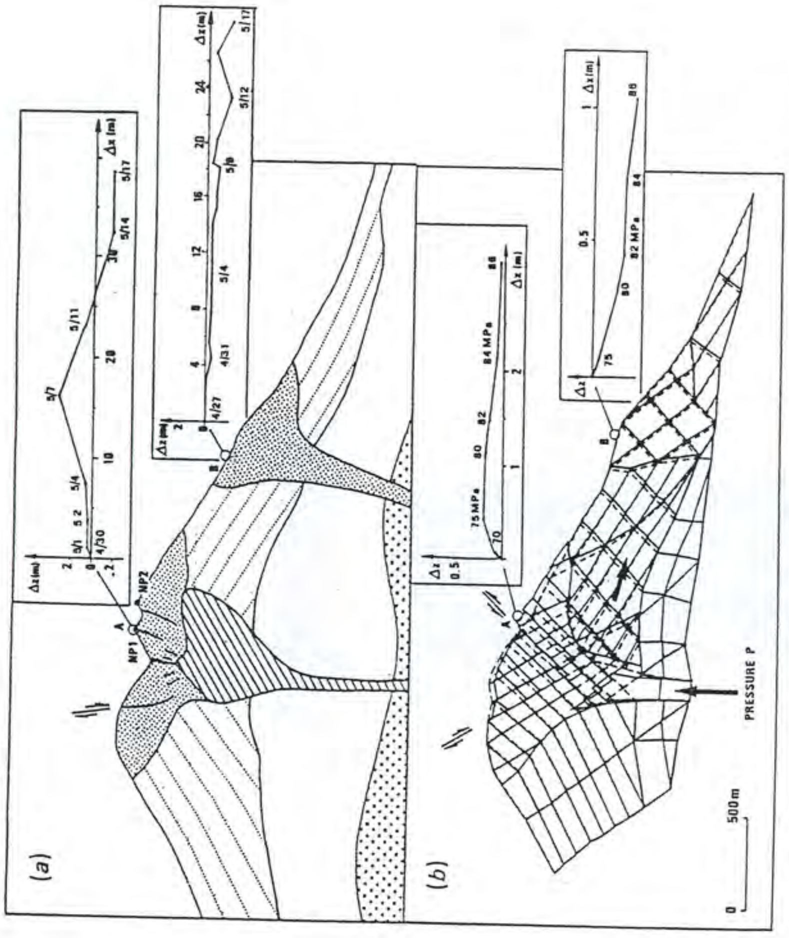

Figure 32. Deformations observed during loading by a magmatic pressure. (a) Cross-section of Mt. St. Helens just before the May 18, 1980 eruption. (b) Modeled deformations of the volcano subject to a magma chamber pressure of 86 MPa (Paul et al., 1987).

too fragile and an internal pressure increase due to magma intrusion, magma-water interaction, or due to earthquakes may produce avalanches and sliding of a large portion of the cone, possibly resulting in a violent explosion similar to that which occurred at Mt. St. Helens in 1980 which blew a large part of the mountain apart.

3. Closed-conduit state structural modeling. A structural model of Vesuvius should be developed for closed-conduit conditions. In this model, account must be taken of the magma chamber boundary conditions (changing volume, pressure, and temperature) and the magma supply through the feeding system. The magma feeding system and immediate magma chamber surroundings should be modeled as viscoelastic or viscoplastic fluids depending on temperature and stresses. Far from these hot surroundings, the rocks should be modeled by an elastic analysis with temperature-dependent parameters, appropriate values for the rock strength, and far field boundary conditions (gravitational and tectonic stress conditions). The closed-conduit structural model must also be properly integrated with the magma chamber domain model, as further discussed in section 6.5.
4. Open-conduit state structural modeling. This model should be an extension of the structural model above. In the open-conduit state it is also necessary to model the changes in the state of rocks surrounding the conduit caused by the ascending magma. This model should also be integrated with the magma chamber and conduit domain models.
5. Structural collapse and formation of caldera. The conduit domain model described in section 6.2.3 should be able to model the structural collapse of the volcanic edifice, where deformations and velocities can be large, more reasonably than a structural model which normally assumes small deformations. Sufficiently far from the central collapsing portion of the conduit, the conduit domain model must be coupled with the structural model described above.

The structural mechanics modeling of the volcanic complex of Vesuvius requires proper definition of a geological model and construction of deformation maps and modeling strategies. The simulation of rocks and soil is a complicated subject due to the mechanical characteristics, *i.e.*, porosity, cracks, *etc.*, that they exhibit. Typical simulations should include the development of a homogenized rock based on singular perturbation techniques which permit to distinguish a macroscale (dimensions of the rocks) and a microscale associated with the size of cracks and/or pores. Due to the disparity between the microscale and the macroscale, it is possible to formulate the governing equations with its constitutive relations for the microscale and use singular perturbations with the perturbation parameter equal to the ratio between the microscale and the macroscale to obtain an equivalent homogeneized medium whose properties are averages of those corresponding to the microscale and macroscale. The validity of such a model should be verified by comparisons with experimental data, and with simple problems such as those corresponding to porous media, and finite cracks in infinite matrix materials. In addition, statistical models for the rocks and soil should be developed in conjunction with homogeneized theory, for the size and distribution of pores/cracks are seldom known. The equivalent homogeneized soil and rocks constitute a homogeneous model which is readily amenable to finite element techniques, even though it may have some stiffness associated with the disparity in the length scales of the pores and rocks. The type of homogenization described above can also be performed when the soil contains small conduits through which water can flow. In this case, an account should be taken for the interactions between the water and the conduits at the microscale, and the governing equations accounting for these interactions should be properly formulated. The equivalent homogeneized model would then account for fluid motions in porous media and the structural mechanics of such media. When the soil is about to collapse due to the reduction of magma pressure below the lithostatic pressure, the homogenized model can be useful since it may consider the inelastic and plastic behavior of the soil provided that appropriate constitutive equations are employed in the microscale, and provided that the homogenized medium equations properly account for non-elastic and plastic phenomena in a non-homogeneous material. The structural mechanics needs should also include the development and validation of a non-isotropic, homogenized medium in order to account for anisotropic effects in soils and rocks. The development of such a model as well as those of homogenized materials requires research efforts in geology and geophysics as discussed in sections 3 and 4.

6.4 Mathematical and Numerical Modeling Requirements

The physical processes associated with magma chamber convection, crystallization, and liquid fractionation; magma ascent in conduit(s), exsolution, fragmentation, and magma-water interaction; elastic, viscoelastic, and viscoplastic deformation of rocks surrounding the magma chamber and conduit; and pyroclasts distribution in the atmosphere and along the cone of Vesuvius are very complex to model. The coupling between different parts of the volcanic system and complicated mathematical expressions of physical laws which model the volcanic transport processes (equations expressing balances of mass, momentum, and energy) present formidable difficulties for the solutions of mathematical equations and require efficient numerical procedures. In this section, the challenges associated with correct formulations of physical laws in mathematical form suitable for numerical solution on computers are presented.

6.4.1 Mathematical Modeling Research Needs

The description of volcanological transport processes can be described adequately by classical physics. These physical laws, expressed in suitable mathematical forms, consist of the continuity or mass balance equation, 1^{st} and 2^{nd} Euler's and Cauchy's laws of motion, and 1^{st} and 2^{nd} laws of thermodynamics. The properties or behavior of different volcanic materials are modeled in physical laws through the appropriate constitutive equations which for multicomponent, multiphase mixtures may be very complex (Dobran, 1991a, 1992b). Modeling of tephra dispersion in the atmosphere requires turbulence modeling of gas and particulates, which may involve two- or four-way coupling as discussed in section 6.2.4. Dense multiphase suspensions may require, however, more complex constitutive equations which account for particle collisions, dilatation, rotation, inertia, turbulence modification of the flow field, *etc.* High temperature rock modeling may require constitutive equations able to describe the elastic, viscoelastic, viscoplastic, and thermal behavior in nonhomogeneous, nonisotropic media.

The physical and constitutive laws which are expressed in terms of partial differential equations must be properly formulated as initial and boundary value problems before they can be solved numerically on computers. To accomplish this task effectively it requires that these equations not only have physical solutions, but also that the solutions be unique. The existence and uniqueness of boundary value problems associated with thermofluid-dynamic phenomena are normally very difficult to prove, especially if the constitutive equations are nonlinear, and it may be only argued that the solutions, if found analytically or numerically, are indeed the physical solutions since they were obtained from equations which model the "reality".

From the above discussion as well as from the discussions in sections 6.2 and 6.3, it is possible to identify the following mathematical challenges pertaining to the proper development of physical modeling equations:

1. Proper formulation of physical laws for multicomponent and multiphase mixtures. While the single-phase flow transport theory is well-established (see, for example, Eringen, 1975), this is not the case for multiphase material continua (Dobran, 1991a, 1992b). In the latter case, the structural properties of mixtures require proper modeling through nonlinear constitutive equations and possibly by additional transport equations expressing these structural properties. The development of such complex models requires the utilization of advanced mathematical tools and single phase (Truesdell and Noll, 1965) and multiphase (Dobran, 1991a) concepts from the modern theory of mechanics. Nonlinear effects in constitutive equations must be, however, introduced selectively to produce *useful physical models* (equations which can be eventually solved effectively and efficiently), since the theory of constitutive equations provides very general expressions which are not very practical

to use.

2. Turbulence modeling of multiphase flows is considerably more difficult than single phase flow turbulence modeling where great advances have been made in this century (Speziale, 1991). Gas-particle, particle-gas, and particle-particle interactions in multiphase flows introduce modeling difficulties in terms of properly formulating the turbulence production and dissipation laws, lack of appropriate experimental data to verify the models, and large number of variables which introduce many different scales of turbulence. Some significant work has already been done in modeling simple two-phase, isothermal, and monodispersed mixtures in tubes and jets. This work, however, is not sufficient for modeling the polydispersed mixtures involved in volcanic columns in the presence of significant buoyancy forces in the atmosphere. Recent numerical simulations of volcanic columns and pyroclastic flows (Dobran et al., 1992; Giordano and Dobran, 1993; Neri and Dobran, 1993) demonstrate very complex flow patterns using a subgrid-scale turbulent model. This model is too simple to capture all important turbulence characteristics of volcanic columns, and should be replaced in future modeling efforts by more complex turbulence kinetic energy/dissipation rate or Reynolds stress models. Turbulence, of course, does not have to be *modeled* but it can be *directly simulated*, if sufficiently fast and large memory computers were available - a task not practically realizable in the foreseeable future.

3. Elastic, viscoelastic, and viscoplastic modeling. The production of the deformation maps discussed in section 6.2.3 calls for the development of appropriate constitutive equations of rocks with different physical properties. Here the required research is concerned with the development of proper mathematical equations describing the stress-strain relationships in three-dimensional stress-strain field and in the presence of anisotropic and inhomogeneous media. A great deal of significant work already exists for homogeneous and isotropic elastic, viscoelastic, and viscoplastic materials which can be employed for the construction of deformation maps. For example, works on viscoelasticity, plasticity, and nonlinear materials by Hill (1950), Sokolnikoff (1956), Christensen (1971), Findley et al. (1976), and Bécus and Cozzarelli (1981), who also discuss uniqueness theorems for many of these materials, should be consulted for further work. Analysis of inhomogeneous media (such as solids containing cracks) can be found in the works of Leguillon and Sanchez-Palencia (1987) and in an edited volume by Sanchez-Palencia and Zaoui (1987).

6.4.2 Numerical Modeling Research Needs

In addition to the mathematical and physical models that must be developed to study the fluid dynamic and structural characteristics of Vesuvius, one must also develop efficient numerical algorithms for solving an extremely non-linear problem with strong couplings between the magma chamber, the conduit, the rocks surrounding the conduit, pyroclastic dispersion, *etc.* Consider, for example, the numerical simulation of phenomena in conduits and surrounding walls. For an accurate representation of these phenomena one should use at least 10000×10000 elements for the surrounding soil and 5000×250 elements for an axisymmetric conduit, in order to properly resolve steep variations of the field variables (Ramos and Dobran, 1993). In addition, erosion phenomena and wall collapse demand the use of adaptive grids. Mesh refinement in this problem may require longer computer times than the solution of the discretized equations which come from finite difference and finite element methods for the mixture and structure. If, in addition, one accounts for processes in the magma chamber, pyroclastic dispersions, lava flows, *etc.*, the number of equations and the required number of nodes increase substantially. Therefore, large amount of computer storage will be required. Furthermore, the strong non-linearities and couplings among different phenomena, and the use of mesh adaption techniques demand the use of fast computers with a great deal of random access memory. The problem has bigger dimensions than those required to solve the flow around an airplane which is being obtained with 1000 MFLOPS (1000 Million FLoating point Operations Per Second) machines even though such simulations include a double-deck structure whereby the solution of the Euler equations is only coupled to that of the boundary layer equations near the airplane. A complete solution of the Navier-Stokes equations for the flow around a complete airplane cannot be achieved with current computers and proper accuracy unless computers with, at least, 1 GFLOPS (1000 MFLOPS) are developed (see section 6.5.1). Since the simulation of volcanoes is much more demanding due to the non-linearities of the problem, diversity of equations and phenomena, and strong, non-linear couplings, it is estimated that, even with computers operating at 1 GFLOPS, one could not obtain an accurate solution of all the physical phenomena which occur in a volcano. However, *an intelligent use* of available computers, performance of numerous numerical experiments, and future computer developments should permit the identification of important physical phenomena where the computational nodes are to be placed at the expense of poorer resolution of those zones where less important phenomena take place. Such an intelligent use of computers will be somewhat demanding in terms of computer storage and computer time, but will be accurate enough for the simulation phenomena if there is a strong interdisciplinary approach to the problem. Furthermore, the large number of equations to be solved requires an efficient implementation of the numerical algorithms for the successful development of a volcanic simulator (see, for example, Carey, 1980; Carey and Oden, 1984; Miller, 1981; Zienkiewicz, 1992; Gropp and Keyes, 1989, 1992). Possible implementations of the numerical algorithms on current and future computers are described in the following sections. It must be pointed out that the successful implementation of numerical algorithms is another interdisciplinary subject which requires strong interactions among applied mathematicians, computer scientists, fluid dynamicists, *etc.*, and that such an implementation requires advances in both software and hardware. In fact, the development of a volcanic simulator would represent great advances not only in volcanology, but also in applied mathematics, computer science, and fluid and solid mechanics.

6.5 Computer Algorithms and Systems Integration Requirements

Efficient simulation of the volcanic system of Vesuvius requires efficient solutions of the physical modeling equations for magma chamber, conduit, soil/rock, and pyroclasts domains on the computer. Each of the domain models requires intensive calculations where the computer resources must be carefully planned and used. Boundary conditions at the domain boundaries couple the domain models in subdomains or overlapping regions (Fig. 33) where the conditions in one domain affect the conditions in the other domain(s), and vice versa. In this manner, a global model of the volcanic system is decomposed into parts by *domain decomposition* (Ramos, 1991), with each domain possessing peculiar characteristic features such as type of modeling equations, numerical solution algorithm, time constants of physical processes, *etc.* Even with domain decomposition, which considerably reduces the complexity of model development and verification, the construction of a simulator for Vesuvius poses serious challenges in the logistics of computer implementation. This logistics is involved in selecting the best paradigms associated with future computer architectures, operating systems, programming languages, and performance tools. Shared-memory, distributed-memory, object-oriented, and functional data flow paradigms are some current parallel computer perspectives that need to be evaluated by any envisaged massively intensive computational application such as a global volcanic simulator for Vesuvius. How the calculations within each domain are carried out, and how the domains are coupled together in an effective computational environment, requires careful considerations of computer algorithms and hardware architectures. In the following, we will place in perspective the future computer trends and suggest research needs aimed at identifying the use of optimal computational resources for the implementation on the simulator.

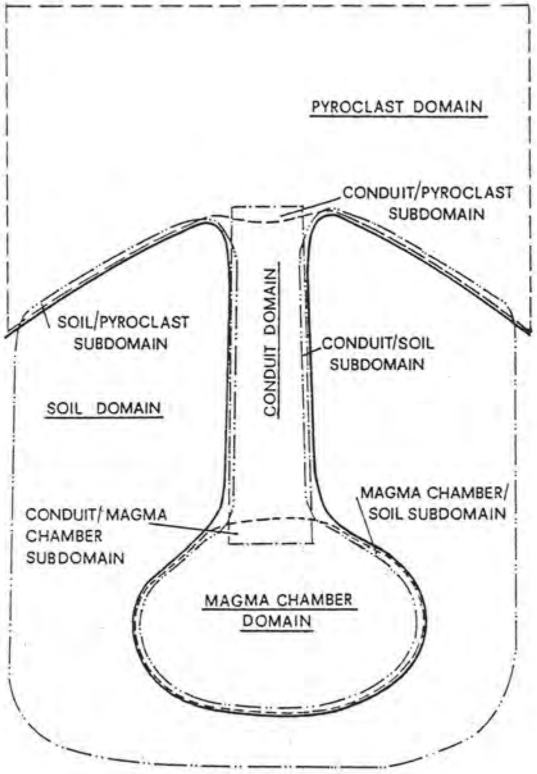

Figure 33. Illustration showing the decomposition of a volcanic system into domains and subdomains for the purpose of numerical calculations and computer implementation (Ramos, 1991).

6.5.1 Computational Requirements and Computer Architectures

The computational requirements associated with the global simulation of Vesuvius parallel those of the grand challenges of the 1990s: climate modeling and ocean circulation; fluid turbulence and viscous flow; quantum chromodynamics; human genome; *etc.* (GC, 1993). All of these challenges require 10 GW (GigaWord) or more of memory and on the order of one TFLOPS (TeraFLOPS or 10^{12} floating point operations per second) of computational speed. By the year 2000, it is estimated that these challenges will be achievable by a computing dominated by SIMD (Single-Instruction-Multiple-Data) and SPMD (Single-Program-Multiple-Data) parallel machines. In a SIMD parallel computer, a single instruction stream is acted upon by many processing elements, in lockstep sequence. One instruction counter is used to sequence through a single copy of the program, and the data that are processed by each processing element differ from processor to processor. Therefore, a single program and a single control unit simultaneously act on many different collections of data. The solutions of simultaneous equations, produced by discretizing the thermofluid-dynamic and structural mechanics transport equations of various domains by the finite-element and finite-difference methods, readily adopt to the SIMD paradigm. SPMD implies running the same *program* but with different data. Here, an entire program is executed on separate data, and because it is possible that different branches are taken within a program, the processors no longer do exactly the same thing in a lockstep manner. Rather, they execute different instructions within the same program. SIMD, therefore, involves one instruction counter, whereas SPMD involves multiple instruction counters. In SPMD, the processors are not tightly synchronized, but are rather synchronized only at the beginning and end of a procedure or section of code that is duplicated on all processors. The processors execute asynchronously within each procedure or identical section of code. A computer program written for a specific application (in our case different domains) should be designed for a particular computer architecture in mind, or the software must be able to adopt to this architecture (see the following section), to optimize the concurrency in computation.

The advantage of domain decomposition is that the computations within each domain can be optimized on one or (many) more processors operating in a suitable parallel arrangement. For some domains, it may be advantageous to use a SIMD paradigm, while for others MIMD (Multiple-Instruction-Multiple-Data), SPMD, or some other approach may be more useful. SIMD may be, therefore, advantageous for the magma chamber domain but not for soil/rock domain with nonhomogeneous rock structure containing cracks. The latter case belongs to the *multidisciplinary models* characteristic of domain models which may be integrated to run on a single parallel machine or on a network of machines performing different functions and exchanging data. Such a distributed computing system may consist of a collection of autonomous computers connected by a communication network. Whether to implement the domain models on a single massively-parallel, general-purpose, and high-speed computer or on a distributed computing environment remains to be carefully studied before the simulator implementation decision is made. As research objectives pertaining to the selection of a single parallel computer or distributed computers in a network to implement the simulator, it is suggested to identify:

1. Single parallel computer architectures suitable for implementing the domain models. Before this task can be accomplished, it is necessary to identify the cost-effectiveness of computation versus the speedup (time to compute a solution to a certain problem using one processor divided by the solution time using many processors in parallel). Parallel processors can be categorized by their interconnection network, by processing units themselves, and as either shared- or distributed-memory machines (Bhuyan, 1987; Bhuyan et al., 1989; Duncan, 1990). Figure 34 gives a summary of interconnection topologies where the distributed-memory designs offer high levels of parallelism through the interconnection of thousands of processors. The dynamic interconnections create links between processors and/or memories on the fly, as the parallel program executes. Static interconnections are fixed by design, and shared-memory architecture typically accomplishes interprocessor coordination through a global memory shared by all processors. The distributed memory machines can interconnect as many as 10^6 processors without major alteration in its basic design (massively parallel computer). A distributed-memory interconnection hypercube can be partitioned into smaller structures that conform to the application's requirements (time-sharing of a large hypercube by different domains). The Intel's iPSC and nCube families of parallel computers on the market today are two leading MIMD machines that use the hypercube interconnection. When the number of processors increases (e.g., the dimension of the hypercube increases), they can be used efficiently in a massively parallel SIMD interconnection. For example, the Connection Machine (Thinking Machines, Inc.) is built this way. Clearly, there are many potential choices on the market *today* for implementing the simulator on a single computer. Tomorrow, this choice will probably increase, bringing unexpected solutions which possibly will lead to the TFLOPS in several years, before the year 2000.

2. Distributed computing environments. In selecting a distributed computing environment, it is necessary to identify the hardware- and software-oriented issues. The hardware-oriented issues of the system include physical networks, hardware measures and fault-tolerance, physical clock synchronization, *etc.* The software-oriented issues include distributed algorithms, resource allocation, distributed operating systems, performance measurement, *etc.* There

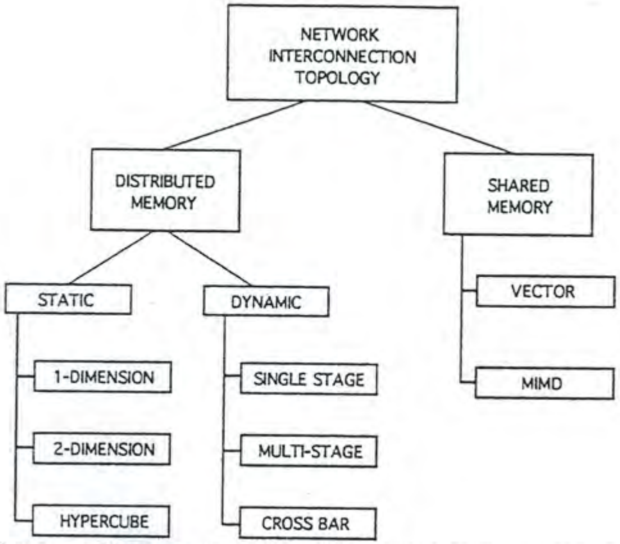

Figure 34. Summary of hardware taxonomy of interconnection network topologies of parallel processors.

are several prototype distributed systems in implementation today: Mach at Carnegie Mellon University, V-Kernel at Stanford University, System R* at IBM, Sprite at University of California Berkeley, VAX Cluster at DEC, *etc.* (Ananda and Srinivasan, 1991; Rai and Agrawal, 1990; Raynal, 1988; Sloman and Kramer, 1987).

Massive parallelism techniques have been around for more than a decade, but only recently has a consensus been reached that it is the only way to build machines of enormous processing rates reaching TFLOPS. Today, the 20 GFLOPS (Intel's Delta and NEC's SX-3/44) performance level has been exceeded. Computers such as CM-5 of the Connection Machine bridge the SIMD and MIMD architectures with processors connected in a *fat tree* in which processors are grouped into clusters or clusters of clusters; and the *mesh* in which processors are arranged in a two-dimensional grid (Fig. 35), is racing steadily toward the TFLOPS.

6.5.2 Computer Algorithms Considerations

In order to meet the grand challenges (GC, 1993) of the year 2000, not only hardware but also software (operating systems) and programming languages for parallel computers must move toward the GFLOPS and TFLOPS ladder. As

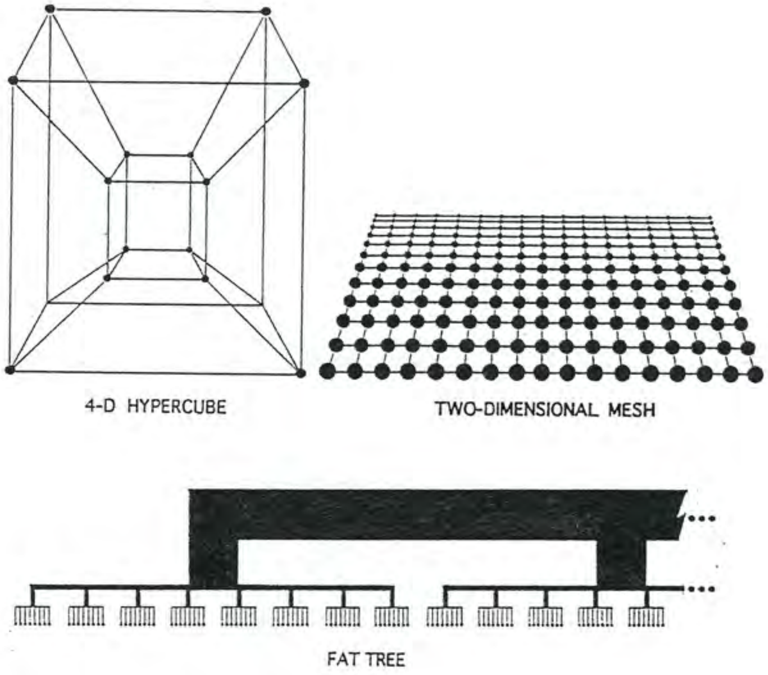

Figure 35. Illustration showing several interconnection arrangements of massively parallel processors. In a 4-dimensional hypercube the processors (black dots) are connected in 4-dimensional hyperspace such that 16 processors can be connected together using only 31 links. In general, an n-dimensional hypercube contains $2^n=N$ processors and there are $\log_2 N$ links at each processor. In a mesh arrangement, the processors are connected in a 2-dimensional grid. In a fat-tree arrangement, the processors are grouped into clusters or clusters of clusters.

envisaged today, grand challenges will be reached if operating systems and programming languages can be made to support multiple architectures.

Unix-type operating systems are envisaged to be the choices for parallel machines. nCube and CM-5 computers run Unix look-alike operating systems and there are several companies in America and Europe which are developing industry-standard versions of Unix. A machine-independent parallel programming language is not yet at hand but great efforts are being made by Cray, nCube, and Thinking Machines toward Fortran 90 and HPF (High-Performance-Fortran) for efficient scientific programming. HPF is planned to include all of Fortran 90 and will add compiler directives to help place and align data in memory so that parallel processors can divide work without conflicts (a preliminary version of HPF is planned to be released in 1993). The ultimate objective is to tailor Fortran that favors no particular parallel computer design and that can be run efficiently on any system, regardless of its particular architecture. HPF will also be able to support applications for networks and workstations. Today, the numerous versions of C language are customized by vendors of parallel machines. In the near future the standardized version of C and object-oriented version of C++ are also expected to be available on parallel computers. All of these trends clearly point in the direction of the transparent use of parallel machines which will bring about unprecedented power and utility for developing a simulator for Vesuvius.

Standard operating systems and programming languages/compilers are not sufficient to support the development of a simulator on parallel computers. Optimum integration of domain models on these computers will also depend on the *tools for application development* that allow programmers to visualize performance and discover bottlenecks. Cray Research is a leader in tools development, and its *atexpert* is an expert system for autotasking or automatic division of a computer program into several parallel processes. Using an X-Window system interface to graphically display data, atexpert can show where a program is spending most of its time and whether these areas are being executed serially or in parallel. A forthcoming tool *xbrowser* is being developed by Cray for viewing and editing Fortran codes. The browser can help a user to insert directives into the code, transform loops into parallel operations, *etc.* Figure 36 summarizes some of the necessary steps for an efficient code generation.

6.5.3 Systems Integration Requirements

Global simulation of the volcanic system at Vesuvius will require massive amounts of calculations and use of computer memory. As seen in previous sections, these problems can be alleviated by performing domain decomposition whereby to each domain a processor on a multiprocessor computer or to a computer in an autonomous system of computers in a network is assigned. Although four principal domains were identified (magma chamber, conduit, soil/rock, py-

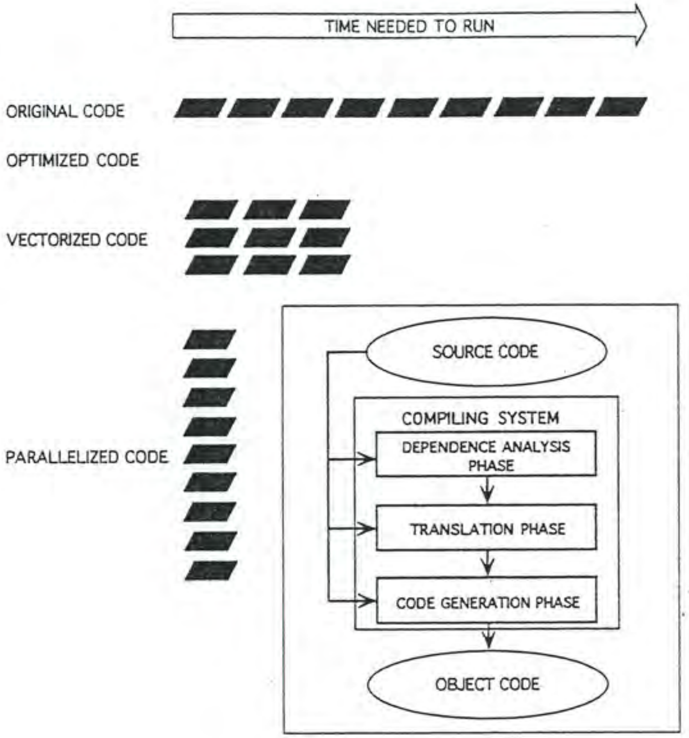

Figure 36. Parallelized code generation strategy. First, the code must be vectorized and then parceled out so that it can run on multiple processors. The today's supercomputers are capable of automating much of this process by analyzing code for independent elements that are parallelizable, translating it into parallel modules, and generating a machine or object code.

roclasts) it was noted that each of these domains requires intensive calculations, and that further domain splitting may be required. In particular, the soil/rock domain may involve very large stiffness matrices not efficient for a single processor, and the pyroclasts domain may require decomposition into a dilute domain to model plinian column and a pyroclastic flow domain to model dense multiphase flows. In defining an optimum simulation time it is thus necessary to consider the *scheduling problem* of parallel computing whereby the computational tasks of solving linear or nonlinear systems of simultaneous equations are scheduled in an optimum manner among the available processors, or where a fixed number of processes is selected to minimize the simulation time.

An *optimum schedule* must determine the *allocation* and the *execution* order of each task such that the tasks can be completed in the shortest time. The scheduling may be static or dynamic. In *static scheduling* each task in the task graph has a static assignment to a particular processor, and each time that a task is submitted for execution it is assigned to that processor. With branches and loops within a computer program, a *dynamic scheduling* of tasks may be more appropriate where the processors are scheduled to tasks depending on demand. By viewing the domains of the volcanic system of Vesuvius as tasks to be assigned to different processors, and different tasks within any domain as subtasks, it may be possible to employ static scheduling to tasks (domain requests) and static or dynamic scheduling of subtasks (requests of processors to handle calculations within a domain). Figure 37 illustrates such a task taxonomy of the simulator. A scheduler/supervisor task carried out by the processor P1 updates the inter-domain conditions in subdomains (Fig. 33) by receiving information from domain processors P2-P5. During each time of the computational cycle, the scheduler processor updates these conditions until a convergence of the global system domain is established. When further splits of domains are required (such as the soil/rock and pyroclasts domains) then the processors of these domains may assume the role of subschedulers. For example, the processors P4 and P5 in Fig. 37 are subschedulers and P6 and P7 are assigned to subsubtasks. When a domain is further decomposed by domain decomposition into subtasks, each subtask can be assigned to static scheduling, and various subsubtasks within subtasks to static, dynamic, or loop scheduling, depending on the numerical solution algorithms. It is thus clear that the system integration issues (which depend on processor interconnection) may profoundly affect the efficiency of computation on a parallel machine.

As further research objectives it is suggested to carry out the following studies:

1. Detailed study of static scheduling using graph-theoretic approach, mathematical programming, and queing theory (see, for example, Chen et al., 1974; Efe, 1982; Stone and Bokhari, 1987). In these studies, it is necessary to establish task graphs and estimate processor execution and communica-

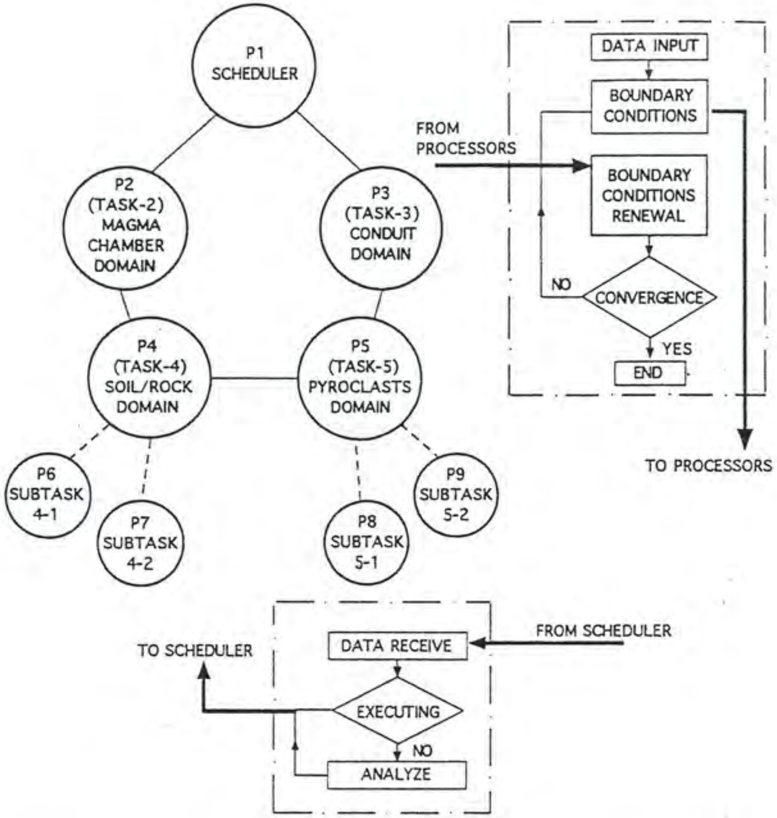

Figure 37. A schematic illustration of processor assignment to various tasks in the global volcanic simulator.

tion times for the global volcanic system domain. The communication delay between processors executing tasks, subtasks, subsubtasks, ..., needs to be carefully evaluated in order to set times for processor execution. Distributing parallel tasks to as many processors as possible tends to increase the communication delay, which contributes to the overall execution time. For this reason, there is a trade-off between taking advantage of maximum parallelism versus minimizing communication delay (El-Rewini and Lewis, 1990). This *maxmin problem* for parallel processing needs to be carefully evaluated during the design stage of the simulator by the performance tools available on parallel computers.

2. Study of problem granularity. *Grains* are tasks within a task graph. If a grain is too big, the parallelism is reduced because potentially concurrent tasks are executed only by one processor. If a grain is too small, however, the overhead in the form of switching, scheduling time, and communication delay is added to the overall execution time. A solution to the maxmin problem defined above can be used to solve the grain size problem.
3. Loop scheduling studies. Loops can be parallelized by assigning different loop iterations to different processors. The factors to be considered in these studies include data dependencies between loop iterations, process load balancing, and overhead due to synchronization and communication between tasks (El-Rewini and Lewis, 1991).
4. Identification of tools for parallel program or systems integration development. In section 6.5.2 we identified atexpert and xbrowser as two parallel computer performance tools of the Cray computer systems. There are many more systems integration tools. These were written for Unix-based workstations and often use X-Windows to produce a graphical user interface. The parallel programming tools can be characterized by the *development phase* of the program, which includes design, code development, debugging, performance analysis, and code restructuring. Some examples of systems integration tools are: ASPAR/EXPRESS (Ikudome et al., 1990); SCHEDULE (Dongarra and Sorenson, 1987), and FAUST (Guarna et al., 1989).

Proper integration of domains and subdomains into an efficient computational environment belongs to the design stage of the simulator. This stage is crucial and should be properly studied and evaluated for alternative solutions. Systems integration studies is, in fact, a feasibility study of the entire computational environment. If not carried out properly, the chances of developing useful volcanic simulations will be rather slim.

6.6 Concluding Remarks

In this section, a great number of thermofluid-dynamic, structural mechanics, mathematical and numerical, and computer research needs have been identified for the purpose of constructing a simulator for Vesuvius. These research efforts require strong interdisciplinary approaches in several branches of science. The production of a physical model of the entire Vesuvian complex will require intelligent and effective solutions of many large-scale problems. In the development of the simulator, an effective strategy may be to study separately the local domain processes of magma chamber, conduit, soil and rocks, and pyroclasts in sufficient detail to understand the physics of these domains. Once this is accomplished, more simple physical models of the domains may be sufficient for use in the global simulator model. Such a strategy must be, of course, very carefully developed, for the global system behavior may involve physical phenomena which have not been tested by the simple domain models. The systems integration issues are so important in the development of an effective and efficient global volcanic simulator that they should not be underestimated.

7. Parametric Studies and Volcanic Hazard-Zonation Research Requirements

The simulator development stages leading to the volcanic hazard-zonation maps shown in Fig. 3 involve the estimation of hazard probabilities associated with different types of volcanic eruption events. This volcanic hazard-zonation assessment approach is not completely *deterministic* since it involves uncertainties associated with the specification of initial, boundary, and constraint conditions of the volcanic system being modeled. For this reason, it is better to employ the word *forecast* rather than *prediction* as being the outcome from the deterministic modeling because the latter word is too precise owing to the uncertainties in the above conditions as well as in approximations made in mathematically representing the physical world. The initial, boundary, and constraint conditions in physical modeling equations must come from volcanological, petrological, geophysical, and other studies as discussed in sections 3, 4, and 5, and can be defined as the *system modeling constraints*. These system constraints enter into the simulator development stages at three different places as shown in Fig. 3: (1) during the inital stage where specific physical models of magma chamber, conduit, soil/rocks, and pyroclasts are developed; (2) during the simulation package definition stage where the domain models are combined; and (3) during the parametric study stage which is associated with the volcanic hazard-zonation maps development. During the initial stage of model development, the system modeling constraints are used to define various volcanological processes which must be modeled by the domain models as well as the data required for the domain model verification. During the intermediate stage of simulator development, where the domain models must be combined into a global system model required for simulation, the system constraints must involve interdisciplinary data from various scientific disciplines, such as volcanology, petrology, geophysics, geology, *etc.*, to define a *simulation package* (Fig. 3). Once this package is defined, the Vesuvian system constraints define once more the range of parameters which must be involved in the simulations and which define the probabilities of various types of eruption styles (tephra falls, lava flows, pyroclastic flows and surges, laterally directed blasts, debris avalanches and lahars, *etc.*). It is important to stress that the system modeling constraints must be established through interdisciplinary efforts (Dobran et al., 1990; Barberi, 1991; Dobran, 1991b; Diez Gil, 1992) which involve very high levels of scientific research.

The parametric studies and volcanic hazard-zonation research requirements can be divided into required studies associated with the definition of the Vesuvian system parameters involved in the simulations, and into the production of volcanic hazard-zonation maps from probability estimates as established from the simulations.

7.1 Definition of the Vesuvian System Parameters

The Vesuvian system parameters consist of the parameters which define the system domains. As research objectives it is suggested to define:

1. Parameters associated with the magma chamber domain. Magma chamber convection, liquid fractionation, and crystallization depend on the magma chamber geometry, magma composition, exsolution and crystal kinetics parameters, melting and solidification parameters, and initial and boundary conditions. These conditions can be constrained from volcanological, petrological, thermodynamic, and other research efforts identified in sections 3-6. In establishing these conditions it is not only necessary to produce averaged values of parameters associated with each scientific investigation but also their variances. The *parameter variances* define the range of possible magma chamber processes. For example, an uncertainty in the magma composition produces an uncertainty in the eruption dynamics as attested by the recent studies of the AD 79 eruptions of Vesuvius and Mt. St. Helens in 1980 (Papale and Dobran, 1992a,b).

2. Parameters associated with the conduit domain. The conduit parameters involve propagating crack and fracture parameters; kinetic parameters associated with exsolution processes; wall erosion, magma-water interaction, and magma fragmentation parameters; bubble growth rates; parameters associated with the geologic system of Vesuvius; deformation maps parameters; and initial and boundary conditions. The parameter variances of the conduit domain help determine different types of volcanic events above a vent. For example, the uncertainty in the conduit wall rock strength can be translated into the uncertainty of wall erosion, which can consequently produce more of less lithic material in magma and lead to a collapsing column producing pyroclastic flows and surges or a plinian column producing tephra falls.

3. Parameters associated with the soil/rock domain. These parameters and associated variances should come from the geological, geophysical, and deformation maps models of the volcanic edifice as discussed in sections 3-6.

4. Parameters associated with pyroclasts domain. The pyroclasts domain involves many thermofluid-dynamic parameters of lava flow, dense multiphase mixtures associated with pyroclastic flows and surges, dilute mixtures of pyroclasts distribution in the atmosphere with turbulent flow conditions, and dense mixtures connected with lahars as described in section 6. These parameters should be carefully evaluated on the basis of past eruption data as discussed in section 3, and further experimental and analytical studies as discussed in section 6.

It should be clear from the above that the uncertainties in the Vesuvian system parameters used in simulations should produce uncertainties in different types of volcanic events. By reducing these uncertainties, the probabilities of good forecasts of the volcanic events will increase. A central goal of the proposed research efforts leading to the development of a simulator for Vesuvius should be, therefore, to reduce the uncertainties of various parameters of the volcanic system.

7.2 Volcanic Hazard-Zonation Maps for Vesuvius

A volcanic hazard-zonation map should: (1) *delimit the zone of hazard related to each type of event*, and (2) *delimit the time of the hazardous event.* These requirements are the "how" and "when" objectives of volcanology as advocated by Dobran et al. (1990). From simulations, the volcanic events can be established as probabilities because the system modeling constraints cannot be ascertained with certainty. The volcanic eruption events consist of lava flows, tephra falls, pyroclastic flows and surges, laterally directed blasts, debris avalanches and lahars, gas releases, *etc.* The objective of a volcanic simulator is not only to forecast different types of volcanic events through probability estimates of these events, but also to produce the *distributions* of these probabilities. For example, a particular combination of the system modeling constraints may produce lava flows which will distribute themselves depending on the *relative probability* of eruption vent locations, flow characteristics, and topography of the volcano. The *hazard*

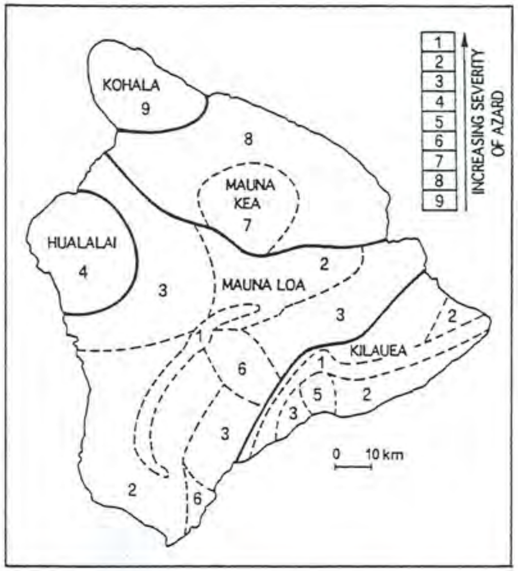

Figure 38. Lava flow hazard-zonation map for the island of Hawaii (Mullineaux et al., 1987).

zones for lava flows can then be based on likely vent locations, topography, flow parameters (lava flow-rate, composition, crystallinity, physical properties), and lava flows from recent geologic past. Figure 38 illustrates a lava flow map for the Island of Hawaii (Mullineaux et al., 1987) which is based on the frequency with which areas have been covered by lava flows during the recent eruptions. A similar map produced by a simulator would be more deterministic, since it would be based on the pre-eruption topography when the lava flows begin exiting from vents, and on the changing topography caused by the flows during the eruption. The lava hazard-zonation maps produced by the simulator may therefore display the distribution of probabilites in space (region surrounding the volcano) and time.

The production of hazard-zonation maps for Vesuvius based on the reference event (see section 1) and simulations of different volcanic processes based on this event was proposed in GNV (1992). The "intensity" and "rapidity" of volcanic processes connected with different events were chosen as the basic criteria for subdividing the Vesuvian area into different hazard zones, defined as zones A, B, C, and "virtual". Zone A corresponds to "intense" and "rapid" tephra falls, pyroclastic flows, mud and lahar flows, toxic gas concentrations, and induced fires. Zone B surrounds zone A and delimits the areas with "strong" tephra falls, whereas zone C, which surrounds zones A and B, may produce local "chaos" among the population due to the produced event(s). The fourth or "virtual" zone would host the collection, assistance, and emergency control centers. The hazard-zonation maps for the Vesuvian area were produced by Osservatorio Vesuviano (OV, 1985) for tephra falls based on the plinian and pyroclastic flow deposits, and for lava flows based on the areas invaded by lava in past eruptions. Figure 39 illustrates these hazard-zonation maps with different probabilities assigned to different areas surrounding the Vesuvius. Using the tephra diffusion model of Macedonio et al. (1988) as discussed in section 6.2.4, Macedonio et al. (1988, 1990) and Barberi et al. (1991) also produced hazard-zonation maps of tephra falls for the Vesuvian area by employing the eruption parameters which are typical of plinian events and statistical wind data profiles of the region. All of the hazard-zonation maps for Vesuvius were produced from the statistical data of past deposits and, therefore, suffer from the basic assumption that the volcano will behave in the future as it did in the past.

The geologic past of Vesuvius should be used only as an *indicator* of its future behavior and not the only approach followed in the construction of hazard-zonation maps. A sufficiently large eruption data set of Vesuvius cannot be produced in the foreseeable future to be useful in forecasting the volcanic events with large probabilities, and even if this data set could be produced it would represent a formalization of ignorance. A statistical approach based on past eruption styles of Vesuvius leaves no room for a change in the eruption style of the volcano which is a definite possibility as the experience has shown with other volcanoes in the past (Peterson, 1988; Tilling, 1989b). The planned approach of producing the volcanic hazard-zonation maps of Vesuvius (GNV, 1992) is inadequate to serve the best interests of the local population. In this approach there are too many uncertainties on the basis of which the civil authorities and individuals cannot produce serious volcanic risk assessments. For example, the Commission identified the reference event as a basis for producing the hazard-zonation maps of Vesuvius without showing that this event corresponds to the *most probable* expected event in the Vesuvian area in the next 20 years. The assignment of probabilities to events is a difficult task and can be carried out properly only after analyzing the effects of the global system constraints (and their variances) in producing these events.

The production of hazard-zonation maps for the Vesuvian area should be based on the *past eruption events as well as on the forecasted events produced by a global volcanic simulator.* As a consequence, these maps should show the time-wise distribution of probabilities of such events as tephra falls, pyroclastic flows and surges, lava flows, debris avalanches and lahars, *etc.* As specific research objectives it is suggested:

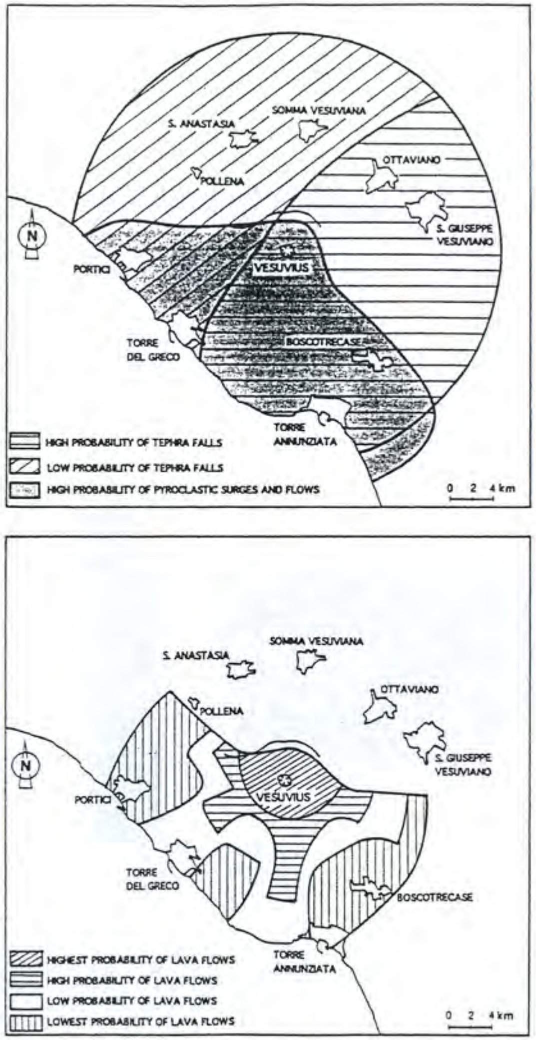

Figure 39. Tephra falls, pyroclastic flow, and lava flow hazard-zonation maps for Vesuvius (OV, 1985).

1. Identification of volcanic events through strategic system parameters variation. The mean and variances of volcanic system parameters should be used by the simulator to produce the spatial and temporal distributions of different volcanic events (tephra falls, pyroclastic flows and surges, avalanches and mud flows, lahars, lava flows, *etc.*). Before selecting the range of parameters for simulations it is necessary to study what is the most effective choice which can produce "good" statistics of different events and minimize the simulation times. For example, it may be useful at first to carry out the simulations with those parameters which have the largest variances, and then proceed with parameters which are better and better constrained, or it may prove most effective to perform simulations with those parameters which produce largest changes in eruption dynamics.

2. Determination of stochastic event processes from simulations. In the experiment or totality of simulations involving the volcanic system parameters, a number $\mathrm{x}(t)$ which is assigned to every outcome of the experiment at time t is a *random variable*. The function x has the domain the experiment and the range a set of numbers assigned to outcomes. If, for example, n changes of parameters produce n_1 outcomes of lava flows in a given area A at time t, then the *probability* of lava flow event in A at time t is the set of experimental outcomes $\{\mathrm{x}(t) \leq x\}$, or in the frequency interpretation of this event this is equal to $F(x,t) = n_1/n$. The objective of computer simulations is then to produce the n*th*-order *distribution function* F which specifies the spatial and temporal distributions of all events, *i.e.*

$$F(x_1,\ldots,x_n;t_1,\ldots,t_n) = P(\mathrm{x}(t_1),\leq x_1,\ldots,\mathrm{x}(t_n) \leq x_n) \qquad (2)$$

   The n*th*-order distribution function F determines all statistical properties of the volcanic events (mean values, correlations, covariances, autocovariances, correlation coefficients, cross-correlations, *etc.*). As further results, it is also possible to produce from the distribution function the *stationarity* properties of stochastic event processes (strict-sense stationarity, wide-sense stationarity, N*th*-order stationarity).

3. Determination of natural hazard-zonation maps for Vesuvius. A *natural hazard-zonation map* is a map determined on the basis of non men-made topography of the volcano. The hazard-zonation maps corresponding to different volcanic events (tephra falls, pyroclastic flows and surges, lava flows, *etc.*) can be obtained from the events stochastic processes by counting the number of parameter changes which produce a given volcanic event in a specific area and at a specific time at Vesuvius. The simulator is simply a filter which maps the stochastic inputs into stochastic outputs.

4. Determination of artificial hazard-zonation maps for Vesuvius. An *artificial*

hazard-zonation map is a map determined on the basis of men-made changes in the topography. These topographic changes in the form of walls, barriers, channels, *etc.* may be introduced into the Vesuvian area purposely to *control* the future evolution of a volcanic event to save both the property and the people. The construction of such maps may be perhaps the most important result from the simulator, since they can also be used by planners, insurance companies, individuals *etc.* for the purpose of *controlling* the urbanization in the Vesuvian area.

5. Vulnerability assessment studies using the global volcanic simulator. A global volcanic simulator cannot be only used for producing hazard-zonation maps in the Vesuvian area, but also to assess the survivability and vulnerability of the men-made structures during different volcanic events. The survivability of various structures can be established by computing the loading forces on these structures due to tephra falls, pyroclastic flows and surges, lahars, *etc.*, and from the knowledge of the structural characteristics of these structures. An approach of this nature for the pyroclastic flows was followed by Valentine and Wohletz (1989b).
6. Determination of volcanic precursors. A properly constructed global volcanic simulator should be able to forecast the important volcanic precursors, such as the volcanic tremor due to magma propagation in cracks, and the deformation of the volcanic edifice. The forecast of volcanic precursors is consistent with the simulator's objective of forecasting the volcanic eruptions.

7.3 Concluding Remarks

A global volcanic simulator of Vesuvius should permit the forecasting of different volcanic events and establishment of probabilities of these events at different places and times in the Vesuvian area. For this purpose, it is necessary to define the mean values and variances of the Vesuvian system parameters which are required by the simulator. The uncertainty of these parameters (variances) define a stochastic input parameter space which a simulator processes in a deterministic manner to produce stochastic volcanic events, or volcanic event probabilities at future times. The results from a simulator can be employed to produce natural hazard-zonation maps, artificial hazard-zonation maps, vulnerabilities of men-made structures, and forecast the volcanic precursors and volcanic eruptions. During a volcanic eruption, a simulator should be able to process input data from different events (such as lava flow characteristics at a vent obtained from direct measurements) and forecast the future evolutions of these events, in a time which is faster than the occurrence of the natural events. In this manner, walls and barriers may be constructed on time to protect the property and humans or gain time for evacuation, as recently demonstrated at Etna (Barberi et al., 1992; Dobran and Macedonio, 1992).

8. Summary and Conclusions

This report has presented a historical essay on the volcanological phenomena at Vesuvius which have appeared in the literature. Most importantly, however, the report has presented a large number of research needs which are required to develop a global volcanic simulator in order to accurately forecast volcanic hazard at Vesuvius. These research needs have been classified into several groups and reflect the interdisciplinary character that research on volcanoes entails. Geological, petrological, and geophysical studies are required to understand the origin and composition of magma and lava flows, presence of aquifers, strength, elasticity and plasticity of magmas, lavas, and surrounding rocks and soils, *etc.* Research on applied mathematics includes the development of accurate models at the microscale and macroscale levels for the magma, lava, soil, and pyroclastic dispersions, and the development of constitutive equations for viscoelastic, viscoplastic, and elastoplastic materials with several phases, inhomogeneities, and anisotropic behavior. Research on applied mathematics also involves research in fluid mechanics, solid mechanics, and numerical methods for solving the large number of governing equations in an efficient manner and for accounting of steep variations of the field variables. It has also been shown that a significant research in computer science is required to take advantage of available and future computers in order to solve efficiently a large system of non-linear, strongly-coupled equations which govern the behavior of magma, lava, soil, pyroclastic dispersion, *etc.*, and that this research demands advances in both software and hardware, and an intelligent use of computers. Throughout the report, it has been shown that an accurate global simulation of the volcanic complex of Vesuvius is an interdisciplinary subject the success of which can only be achieved by frequent, critical, and intelligent interactions amongs those working in geology, petrology, geophysics, applied mathematics, fluid and solid mechanics, and computer science. The development of a global volcanic simulator for Vesuvius would not only benefit the Vesuvian area populations but also the scientific community because of a high level of research that such a development requires. Those who are responsible for the present and future wellbeing of the population in the Vesuvian area should realize that by developing a simulator for Vesuvius they may be avoiding a future genocide.

> Com'io divenni allor gelato e fioco,
> Nol dimandar, lettor, ch'io non lo scrivo,
> Però che ogni parlar sarebbe poco.
>
> Dante, inf. XXXIV.

Uncharted orbits call me, new dominions
Of sheer creation, active without end.
This higher life, joys that no mortal won! ...
Upon the mild light of the earthly sun
Turn bold, your back! And with undaunted daring
Tear open the eternal portals
Past which all creatures slink in silent dread.
The time has come to prove by deeds that mortals
Have as much dignity as any god ...

Goethe (1749-1832), Faust.

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APPENDIX

MAGMA AND LAVA FLOW MODELING AT ETNA

Commission of the European Communities
Sponsored Research Program (1993-1994)

1. Introduction

Following the CEC's recommendation, the proposals "Magma and Lava Flow Modeling of Hazards Assessment at Etna" and "Definition of the Fine Structure and the Plumbing System Aimed at Eruption Prediction, Hazard Assessment, and Eruptive Mechanism Understanding" have been combined into a single proposal with the title "Magma and Lava Flow Modeling and Fine Structure and Plumbing System Definition Aimed at Hazard Assessment at Etna" and will be coordinated by Prof. Flavio Dobran. The combined proposal retains the objectives of the original proposals. The project involves 7 groups, with participants from Italy, France, and England.

The overall objective of the proposed research is to produce data and computer programs which can be used for assessing the volcanic hazard at Etna. This work will be accomplished through interdisciplinary studies involving geologists, geophysicists, volcanologists, physical modelers, and numerical modeling experts.

The data will be used for verifying the numerical models of magma and lava flows and will include: data pertaining to crack propagation with and without magma-sustained flow; data pertaining to dykes; effusion rates, temperatures, compositions and rheologies of past and new eruptions and correlation with dyke geometry, seismic data and petrology; and local and general lava flow field data pertaining to ephemeral mouths, structure of crusts, tunnels, leveés, and flow heads. The numerical models will include modeling of enlargements of cracks caused by hydrodynamic, acoustic and thermal effects of the uprising magma, magma flow modeling with non-Newtonian rheology in the presence of melting/solidifying walls, thermoviscoelastic modeling of the conduit wall, thermoviscoelastic modeling of lava flow heads and crusts, and three-dimensional and global modeling of lava flow. The magma and lava flow models will be verified separately with past and new eruption data, and the models will be integrated into a single numerical model which should be able to simulate the magma ascent in conduits and lava flows during an eruption of Etna.

The realization of the data gathering and modeling objectives will permit an assessment of the lava flow hazard at Etna and will also include data from other Etna projects: the seismic tomography project, degassing and volatile budget project, and geophysical study on the plumbing system and temporal evolution project. The last year of the project will involve the lava flow hazard evaluation with the global model. This evaluation will be based on the pre-defined hazard parameters and actual topography of Etna.

2. General Methodology

The determination of past eruption data will involve examinations of geological and geophysical literature to establish crack and rock fracture data related to magmatic processes at depth. In the event of an eruption at Etna, measurements of the vertical velocity of the jet at the vent will be accomplished with a sodar or acoustic sounder. The viscosities of magma and lava will be measured with a motorized shear vane viscosimeter, whereas the temperatures with thermocouples and infrared radiometers. Prior to use in the field, all instruments will be calibrated. The lava flow effusion rates will be measured using the lava flow velocities at the surface and flow channel dimensions. The velocity profiles will be measured across the active lava flows following markers left on the free surface and by analysing frame by frame from video records. The chemical and textural composition of magma and lava will be measured by using a scanning electron microscope and by the energy dispersive spectrometer. The crystal and vesicle size distributions will also be established, and the whole rock chemical composition will be determined using X-ray fluorescence and absorption spectrometry. The lava flow physical and rheological properties will be measured at the vent and at, at least, two different locations downstream. Measurements will also be made of the lava bulk-flow field dimensions as well as of the topographic variations of the underlying and surrounding terrain during the course of an eruption. Measurements of local lava flow structures and their variation with time (channel and margin dimensions, ephemeral mouths, *etc.*) will also be made. The overall growth of active flow fields will be monitored with airborne support by following changes in flow-field morphology with time and position.

Modeling of the enlargement of an initial crack at depth will be studied by fluid mechanics and energy transport equations. These equations will be solved numerically be finite difference methods and will permit an assessment of the hydrodynamic, acoustic, and thermal effects on crack propagation and formation of a conduit for magma flow. The magma flow in conduits with wall melting/solidification will involve a solution of two-dimensional fluid mechanics and heat transfer equations by means of an adaptive finite difference method which maps the unknown, time-dependent flow field into a unit square. As a first approximation, the viscosity in the model will be assumed to increase exponentially as the magma temperature approaches the solidification temperature, whereas subsequently a stress constitutive equation which accounts for the non-Newtonian, elasto-viscoplastic behavior of the magma and rocks will be introduced. A thermoviscoelastic model of rocks will be implemented in a staged manner, and the rock and magma flow models will be combined into a unified model and verified with data. The rock and magma flow modeling equations will be solved by a finite difference or a finite element method, depending on a careful evaluation of strategies.

Lava flow heads and crusts will be studied by developing thermoviscoelastic flow models. These models will permit the development of "lava rules" which will be used in a global model of lava flow. A three-dimensional transient lava flow model will also be developed which will allow for lava solidification and formation of lava crusts due to heat transfer from lava to the ground and from the crust to the environment. The results from this model will also be used to establish modeling lava rules for use in the global lava flow model. The global lava flow model will involve an efficient simulation of lava flows over large distances. This model will be quasi three-dimensional and involve three layers: the (inner) layer near the ground, an intermediate non-Newtonian (core) layer, and a viscoplastic (crust) layer in contact with the atmosphere. The global lava flow model can be solved by means of a weighted residuals technique combined with finite difference equations for the thickness of each of the modeled layers. The full three-dimensional model requires that special attention be paid to the selection and implementation of a numerical scheme because of the nonlinear character of the modeling equations. Both finite element and finite difference methods will be considered in this regard.

3. Deliverables

1. Technical and final reports will be presented by each of the participants to the coordinator and CEC.
2. Synthetic progress and final reports will be produced by the coordinator for CEC.
3. Copies of scientific publications, fully or partly resulting from the project, will be sent to the CEC.
4. Computer programs for the assessment of volcanic hazard at Etna will be produced.
5. Detailed description of the new instruments developed on the project and their calibration tests data will be made available.
6. Map of Etna with indication of main faults and fissures, parasitic cones, earthquake epicenters and geochemical spots, related description and annexes will be produced. Furthermore, a technical report on the petrological constraints to the plumbing system will also be prepared.

IMPRESSO NELLE OFFICINE DI AGNANO PISANO DELLA
GIARDINI EDITORI E STAMPATORI IN PISA

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Aprile 1993