Volcanoes of Europe

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Volcanoes of Europe

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Preface

olcanoes pay no attention to human foibles such as historical periods, political boundaries and scientific definitions. Thus, the title *Volcanoes of Europe* disguises several kinds of arbitrary choices. We have included, for instance, the Canary Islands and the mid-Atlantic islands of Jan Mayen, Iceland, and the Azores within the European umbrella, although two of the Azores and half of Iceland belong to the North American plate, and the Canary Islands belong to the African plate. On the other hand, we do not describe the volcanoes of Turkey and the Caucasus, which many would, no doubt, call European.

It is altogether more difficult to define those volcanoes which are active, dormant, or extinct. Volcanoes do not always display the secrets of their past, nor do they always reveal their future intentions. Several times, even in the course of the twentieth century, expert volcanologists have been puzzled – not to say surprised – when certain volcanoes have suddenly burst into life after a long period of calm.

Clearly, an erupting volcano is active. But such a definition would restrict the European field to Stromboli and Etna. Equally, a volcano such as the Cantal, in central France, has not erupted for many millions of years and is in all probability extinct. But, of course, volcanoes do not all behave in the same way. The eruptions that form cinder cones rarely last for more than a few years, and then fall silent forever, but the violent outbursts of many stratovolcanoes have been limited to short spells between long periods of repose that have occurred, on and off, for thousands of years. Moreover, active volcanoes rarely grow up in isolation. Many now rise from much older volcanic bases. Thus, to set recent activity in its proper context, it is often necessary to extend the volcanic story well back into the geological past. Even hyperactive Stromboli cannot be fully understood if only its recent eruptions are considered. Thus, the ill defined grey areas between the definitions of active, dormant and extinct demand arbitrary choices.

We therefore consider that a volcano can be designated as active if it has had a magmatic eruption during the past 10 000 years. This is the same definition as that adopted by Simkin & Siebert (1994) in the second edition of their *Volcanoes of the world*. This obviously arbitrary date has the advantage of being long enough to encompass most eruptions during postglacial time, but is also short enough to eliminate areas where the only suggestions of eruptions come from barely substantiated legends. But even this definition has its drawbacks. For example, many vents that erupted cinder cones during this period are unlikely to erupt again. May an indulgent reader, then, accept them as the exceptions that prove the rule.

The notion of historical time is also extremely flexible, and historical records count for little within the defined span of 10 000 years. Even within the limited European context, the period during which eruptions could actually be recorded has varied greatly from place to place. Probably no volcano on Earth has a longer recorded history than Etna, where eye-witness accounts have recounted its eruptions, with admittedly varying degrees of fantasy, for 2500 years. However, the Italian volcanoes were in an exceptionally favoured position in the classical world. On the other hand, records in Iceland extend back only to the early centuries after the settlement in AD 874, and no human being even settled in the Azores until 1439.

But there are historical records and historical records. Most reports of eruptions share the defects of all ancient accounts. The series is incomplete, errors are repeated, descriptions are exaggerated, facts are twisted to fit preconceived notions, references are too brief, too vague and often just untrustworthy. Moreover, many volcanoes erupted in what were, for long periods, remote areas; the very mention of an eruption depends on the knowledge of the author, or those from whom the author is copying, on the survival of texts, the spread of news and so on. Repeated mentions do not mean that a volcano was in constant agitation, but neither does the absence of information indicate that a volcano was dormant. Indeed, most historical records achieve only a modicum of reliability at the beginning of the nineteenth century.

Beyond the historical context, accurate dates of eruptions are only just becoming available in many areas. The traditional methods of geological dating by fossils and stratigraphy are very hard to apply to volcanic edifices. The timespan is too short; the volcanic products preserve few animal or vegetal remains; and the erosion of valleys and their subsequent occupation by further lavas make large and active volcanoes a stratigrapher's nightmare. In many cases, too, the most recent eruptions have masked the products of their predecessors to such an extent that the story of the volcano can scarcely be elucidated at all. At least, monogenetic cinder cones and lava flows invite the gratitude of volcanologists by their broad simplicity.

In recent decades, new techniques of absolute dating have done much to overcome these handicaps. Radiocarbon dates have been calibrated with greater precision, and volcanic rocks can be dated by thermoluminescence, potassium–argon, and palaeomagnetic and archaeomagnetic studies. A whole range of these techniques is now being applied, especially to those more dangerous volcanoes whose tempestuous past must be discovered before their future furies can be predicted with accuracy. Nevertheless, the absolute dates of many European eruptions have yet to be established.

A geomorphologist is often tempted to assess the age of volcanic features by their appearance and by the relative amounts of weathering and erosion that they seem to have undergone. However, the speed of degradation depends upon many conflicting factors, including the varying power of the atmospheric elements, and the different strengths of the rocks that they attack. In general, as with human beings, young volcanoes have fresh features and svelte, sharply defined outlines, whereas older volcanoes are blunted and scarred by innumerable gullies. Sometimes such analysis is valid, as many instances in the text might demonstrate, but judging the age of a volcano in this fashion is fraught with difficulty and it involves an unavoidable element of subjectivity. Such morphological exercises that have been tried here should be regarded as a last resort in the attempt to provide a coherent history of a volcanic area.

The availability of information is a further element that imposes its own limitations on any treatment of European volcanoes. In spite of the boom in volcanological research during the past few decades, some volcanoes are still imperfectly known. Thus, several Italian volcanoes are in intensive care, whereas those in the Azores, for instance, have undeservedly progressed little beyond the waiting list. Consequently, the balance and the treatment of active European volcanoes is, in part at least, influenced by the amount of the scientific literature that is available. Our work therefore indicates not only the broad state of knowledge at the end of the twentieth century but also highlights where some fruitful research could be accomplished. But the chief aim of this study is to stimulate a wide range of readers – to encourage them to take an active, informed interest in some of the most sublime and fascinating features in the natural world – and, especially, to go and see them. Aesthetic rewards will also enhance their scientific pilgrimages, because the European volcanoes embellish landscapes beyond compare.

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Jean-Claude Tanguy was primarily responsible for the sections on Etna, Vesuvius and Pantelleria. Alwyn Scarth bears the responsibility for the remaining chapters; he gratefully acknowledges the invaluable assistance of Juan-Carlos Carracedo, Victor Hugo Forjaz, Harry Hine, Maxime Le Goff, and especially Anthony Newton.

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PART 1 INTRODUCTION

1 Introduction

The distribution of the volcanoes of Europe is perhaps more difficult to understand than on any other continent because of the complications caused by the collision between the Eurasian and the African **plates**.* Most of the volcanoes occur on the margins of the European continent: in the Mid-Atlantic Ridge, the Canary Islands, southern Italy, and the Aegean Sea. The remaining areas of volcanic activity are broadly associated with old rifts in France and Germany. Thus, some **eruptions** are related to the growth of the Eurasian plate along the Mid-Atlantic Ridge; others are related to collision and subduction linked to the clash between Europe and Africa; some eruptions seem to be associated with **hotspots**; and others to the presence of deep fractures transecting the Earth's **crust**. But, in spite of all the remarkable advances made in volcanology in recent decades, it is still sometimes difficult to explain the exact position of some quite important European volcanoes.

The volcanoes on the Mid-Atlantic Ridge are clearly linked to the growing edge of the Eurasian plate. Eruptions are largely submarine and continuous along the whole length of the Ridge, and they were unseen and, indeed, largely unsuspected, until research in the past few decades revealed their enormous importance in the dynamics of the Earth. These eruptions occur chiefly from multitudes of **fissures** that produce the basalts that make the world's oceanic crust. In Jan Mayen, Iceland and the Azores, the crest of the Mid-Atlantic Ridge and part of its flanks have been built up above the waves, so that this vital volcanic activity can be inspected and analyzed at close range. However, the emissions on these islands are not wholly basaltic, and they have also included eruptions of more evolved **magmas** after reservoirs have developed. But, although the Canary Islands, which lie on the African plate, seem to have been generated by a complex hotspot, no fully satisfactory explanation for the details of their formation has yet emerged. Practically all the volcanic islands in the North Atlantic Ocean represent considerable accumulations of **lavas**. Their bases often lie more than 2000 m deep on the sea floor, and several volcanic peaks rise more than 2000 m above the waves. Thus, Beerenberg in Jan Mayen, Öraefajökull in Iceland, Pico in the Azores, and Teide in the Canary Islands, form some of the most prominent mountains in the North Atlantic Ocean – and are, at least, on a par with any volcanic piles in the rest of Europe.

The volcanoes in Italy and Greece are closely linked to the prolonged collision of the African and Eurasian plates, during which several microplates detached themselves from their parent masses and pursued varying and independent courses. At the same time, the edges of the microplates and the Eurasian plate were smashed, fractured and crumpled as the African plate advanced broadly northwards. Thus, continental sediments carried on the plates were thrust up and contorted to form the Atlas Mountains, the Alps, the Apennines, and the chains of the Balkans, Greece, and Turkey; and magma made its way to the land surface up major faults that transect the Earth's crust. Etna and Vesuvius might have formed in this way. Parts of the forward edges of the African plate were also

* Words in bold type are explained in the Glossary (p. 219).

subducted beneath the Eurasian plate and the adjacent microplates. This subduction caused the eruptions that formed the Aeolian Islands and the volcanic islands in the Hellenic Arc in the Aegean Sea. Subduction is thus probably responsible for the most violent European eruption during the past 4000 years, on the Greek island of Santoríni, and for the world's most diligent volcanic performer in modern times, Stromboli. But these Mediterranean volcanoes are as varied as the tectonic conditions that have given them birth. Some, such as Etna and Stromboli have long histories of moderate and mainly basaltic eruptions; others, such as the Fossa cone at Vulcano, have erupted tuffs in more vigorous outbursts; yet others, such as Santoríni and Vesuvius, have erupted huge volumes of **fragments** (pyroclasts) during episodes of great violence that buried whole cities.

The third main group of European volcanoes formed broadly in relation to the discontinuous rifts that traverse the continent from Oslo, in the north, to the Rhine Rift Valley and on to the Limagnes of central France. Eruptions have given rise to many cones and **maars**, in both the Eifel Massif in Germany and the Chain of Puys in central France.

The Mediterranean volcanoes

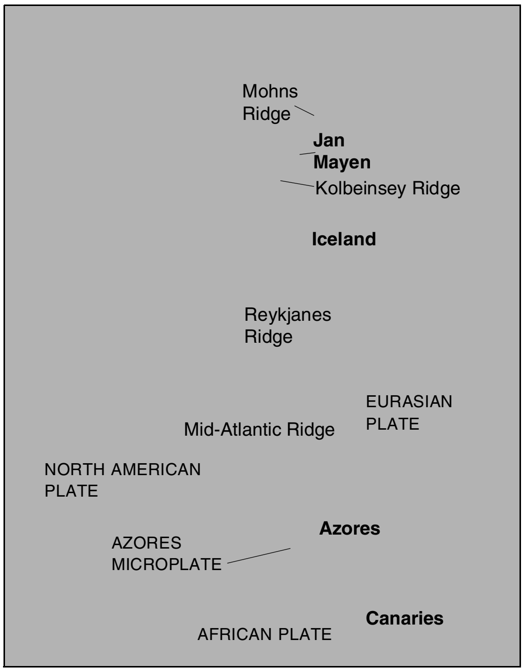
The volcanoes and the major fold structures of the Mediterranean area have been caused fundamentally by the collision between the Eurasian and African plates (e.g. Dercourt et al. 1985). However, this generalization hides a great complexity of events that perhaps has no equal anywhere else on Earth. Although the Mediterranean area has been intensively studied, much work still needs to be done before the intricacies of the scenario of its development can be truly unravelled. It is thus difficult to explain the distribution and the causes of the Mediterranean volcanoes without making generalizations that may prove to be misleading, inadequate or even inaccurate as research progresses.

The collision takes place between two plates carrying continents that are themselves directly involved in the impact, which has shattered their edges, formed microplates that have moved in different directions, and crumpled and faulted the rocks for millions of years. Thus, collision has not only brought about subduction and deep faults that transect the whole crust, but also areas of crustal extension. As a result, individual Mediterranean volcanoes can have several different causes or, indeed, combinations of causes. In broad terms, subduction seems to be responsible for the Greek volcanoes on the Hellenic arc in the Aegean Sea, and for the volcanoes in the Aeolian Islands, whereas Etna and Vesuvius perhaps owe their growth to eruptions at the intersection of deep major faults. But the relationships are far from simple and the specialists rarely agree about the exact details of the course of events.

With this varied tectonic background, it is not surprising that the Mediterranean volcanoes have displayed virtually the complete range of eruptive styles. Thus, Vesuvius has been extremely violent, often erupting **Plinian columns** and **nuées ardentes**, but was largely effusive from 1631 to 1944; Etna has been chiefly effusive, but had some violent outbursts about 2000 years ago; Stromboli has been mildly explosive for many centuries; and Santoríni has produced only moderate eruptions since its great explosion in the Bronze Age. And all the while, thousands of less spectacular eruptions have formed **cinder cones**, lava flows, **domes**, **fumaroles** and mudpots, which have been feared ever since antiquity. Italy is the zone of greatest tectonic complexity. And it has also been the forum of the greatest, most varied and most closely studied volcanic activity in Europe.

The Mid-Atlantic Ridge

The Mid-Atlantic Ridge is the most clearly defined, and probably the best known, of all the **mid-ocean ridges**. It forms a sinuous curve bisecting the Atlantic Ocean from the Arctic to Antarctica, in a continuous chain of volcanic accumulations rising 2 km or more from the ocean floor. A longitudinal rift runs along its crest, which marks the site of continual volcanic eruptions, where oceanic crust is generated as the North American and Eurasian plates diverge. The main source of these eruptions is the multitude of fissures and **dykes** that run parallel to the trend of the crest. They have provided the basaltic **pillow lavas** and the black smokers that are characteristic of this environment. Generally speaking, the youngest volcanic rocks occur at the higher, central parts of the ridge, whereas increasingly older rocks are found in roughly parallel strips farther and farther from the crest.



The plate boundaries and volcanic islands of the North Atlantic Ocean.

The ridge is mostly submerged and it is only in exceptional circumstances that volcanic eruptions are so frequent as to have built it above sea level. The most common explanation for these exceptional conditions is that a **mantle** hotspot lies beneath the mid-ocean ridge and this seems to be the most likely reason for the emergence of Jan Mayen, Iceland, and the Azores as some of the culminating points on the Mid-Atlantic Ridge. Jan Mayen lies on the Eurasian flank of the ridge; Iceland is transected by the ridge so that its western part belongs to the North American plate and the eastern part to the Eurasian plate; and the ridge divides the Azores.

Finally, the Canary Islands are apparently not related to the Mid-Atlantic Ridge, but may have been initiated in part by the collision between the African and Eurasian plates. But they bear no evidence of subduction and seem to have developed chiefly in response to one or more hotspots beneath the African plate.

The study of the islands also shows significant variations from this simplified pattern. Major offsets develop in the trend of the Mid-Atlantic Ridge that are associated with notable transform faults and fracture zones more or less at right angles to the trend of its crest. One of their broad effects is to create further fissures up which magma can then rise. They also tend to facilitate activity on the flanks of the ridge, where eruptions can build up and widen the ridge itself. Thus, the Azores rise from a broad submerged platform on the flanks of the ridge. The rocks on these flanks usually increase in age with their distance from its crest, but the materials emitted during the flank eruptions are much younger than the rocks upon which they lie and they do not usually increase in age with their distance from the crest of the ridge.

The morphology of the Mid-Atlantic Ridge is further complicated near the Azores by the development of a triple junction. Rifting occurs not only between the Eurasian and North American plates but also between the Eurasian and African plates. A zone of secondary spreading seems to have developed and may have formed a microplate supporting the central and eastern Azores.

The fourth rather abnormal feature of the ridge is the eruptions from central clusters of **vents**, which are often related to flank volcanism. In Iceland, for instance, they often form large basaltic **shields** and **pahoehoe** surfaces, but sometimes more explosive eruptions take place if the magma has undergone some evolution in a reservoir. In these conditions, the prevalent **basalts** are replaced by intermediate lavas such as andesites or even **rhyolites**. At the same time, lava flows become less numerous and fragments become increasingly important as a **stratovolcano** is constructed. In this way, Hekla and Oraefajökull, for instance, have grown up in Iceland, and Beerenberg in Jan Mayen. In the Azores, most of the stratovolcanoes have also undergone a markedly explosive phase that led to the formation of large **calderas** on their summits. Iceland, too, has more than a dozen calderas, some of which, like Grímsvötn, are hidden beneath ice caps.

Iceland is by far the largest emerged zone of any mid-ocean ridge in the world, and it is the best studied of the three European components of the Mid-Atlantic Ridge. The growth of the much smaller and less complex island of Jan Mayen has also been broadly elucidated. In the Azores, where the mixture of eruptions is greater, several important detailed studies in recent years have begun to clarify the picture of their development.

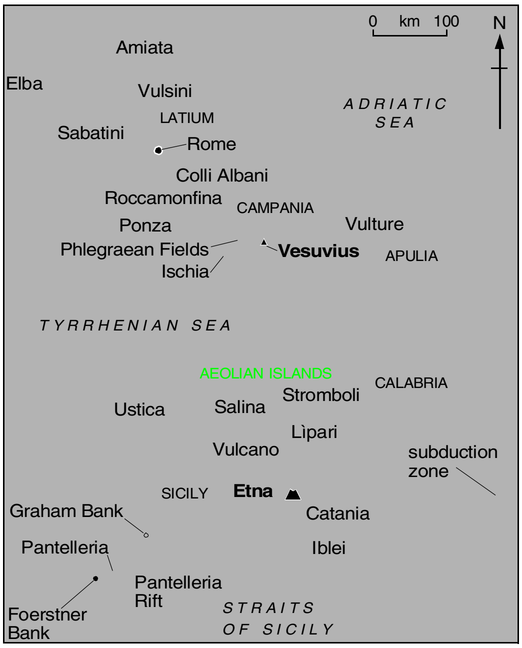
PART 2 THE MEDITERRANEAN

2 Italy

ulcano, Stromboli, Etna and Vesuvius are the most famous active volcanoes on Earth. It is the Italian volcanoes, more than any others, that have given the Western world its views, fears, fascination and preconceived notions about volcanic activity for over 2000 years. Entangled with myths, deities, devils and saints, their varied and often spectacular eruptions have always inspired terror and fascination. The continual eruptions of Stromboli fully justify its nickname, "Lighthouse of the Mediterranean"; Etna probably served as a model for the Polyphemus story in the Odyssey, and its emissions have often been televised in the past few decades. The awesome powers of Vesuvian outbursts were immortalized by Pliny the Younger in AD 79 and, ever since, have forced many a Neapolitan sinner to the confessional. Vulcano itself, the forge of Vulcan, has stamped its name on practically every European language. The renown of the Italian volcanoes has sprung from centuries of intimate contact and observation by a large population that has clustered, in spite of all the dangers, on the rich soils of their flanks. The Seven Hills of Rome, too, were carved from old volcanic products, whereas Pompeii and Herculaneum were later buried by others.

The volcanoes of Italy take a whole gamut of forms, from calderas and stratovolcanoes to cinder cones, domes and mudpots. Their eruptions have ranged from vast **Plinian** outbursts with **nuées ardentes**, to lava flows and **solfataras**. Their products similarly cover a wide volcanic spectrum, from a predominance of basalts in Sicily, to the concentrations of potassium-rich rocks, **trachybasalts**, **tephrites**, **trachytes**, **latites** and **phonolites**, as well as **rhyolites**, in peninsular Italy. The active volcanoes have themselves strikingly different personalities and behaviour. Etna, Vesuvius, Stromboli and Vulcano are distinctive members of the volcanic family and, as a result, their activity has often been used to establish archetypes for a basic classification of styles of volcanic eruption. Long familiarity and study has also given Italy many type-localities, and Italian is a major source of technical terms. **Strombolian**, **Vulcanian**, **lapilli**, scoria, fumarole, solfatara, latite, atrio, not to mention volcano, provide just a few examples out of many. It is not surprising, therefore, that Italy has become the scene of some of the most vigorous contemporary volcanic research from several European countries. The progress of science has generated a vast bibliography. But, although the histories of many active and recently extinct Italian volcanoes have been elucidated, many intriguing problems about them have yet to be resolved, not least of which are those concerned with the very causes of Italian volcanic activity.

In the present state of knowledge, Italy seems to be an unusual volcanic environment: an area of continent-to-continent collision, manifest in large and frequent earthquakes; with widespread, but not always clear, subduction; with crustal extension following upon compression and the development of deep fractures; with magma often of high potassic content, and also perhaps derived from the crust in some areas and from the mantle in others, with the opportunity for differentiation as well as contamination en route. The uncommon combination of these features is a major warning against taking the Italian volcanoes as archetypes and extrapolating their



The volcanic zones of southern Italy.

characteristics to the different outside world. In any case, they have enough individuality to merit all, and more, of the close study that they have always received.

The volcanoes of Italy stretch in a broad but discontinuous band along the western flanks of the Apennines from Tuscany to Campania alongside the Bay of Naples and on, through the **seamounts** of the Tyrrhenian Sea, to the Aeolian Islands and eastern Sicily. In addition, isolated outposts occur in Sardinia, the Euganian Hills in the Po Valley, in Monte Vulture in Basilicata and in the island of Pantelleria in the Straits of Sicily. In a very general way, volcanic activity started in the north and spread irregularly southwards. Thus, the northern areas seem to be wholly extinct, whereas many of the southern areas are clearly still active.

The intense orogenic crumpling of the Apennines was followed by tensional movements that were concentrated on the western margins of the Apennines and were probably connected to the opening of the Tyrrhenian Sea and the continuing collision of the African and Eurasian plates, and of the microplates between them. Deep fractures could then sometimes provide an easy path for rising magma that perhaps played a major role in the eruptions of Campania, Monte Vulture and eastern Sicily. It was probably only southeast of Calabria that the collision was accommodated by the development of a **subduction zone** that gave rise to the volcanoes of the Aeolian Islands. The intensity and types of fracturing, the varying natures of the magmas and their different rates of ascent, then produced distinct regional patterns of volcanic activity. Thus, the volcanism that is only recently extinct or is still active at the present time falls into five main zones: Tuscany, Latium, Campania, the Aeolian Islands and Sicily.

Most of the volcanic areas of Tuscany are small, scattered and eroded, and were formed between 5 million and 2.3 million years ago. However, Monte Amiata, much the youngest and largest volcanic area in Tuscany, dates from less than 400 000 years ago. Although Tuscany has no active volcanoes at present, the magmas still warm the waters circulating in the upper layers of the crust. This heat is harnessed at Larderello and Monte Amiata to such an extent that Tuscany is one of the most important sources of geothermal energy in Europe.

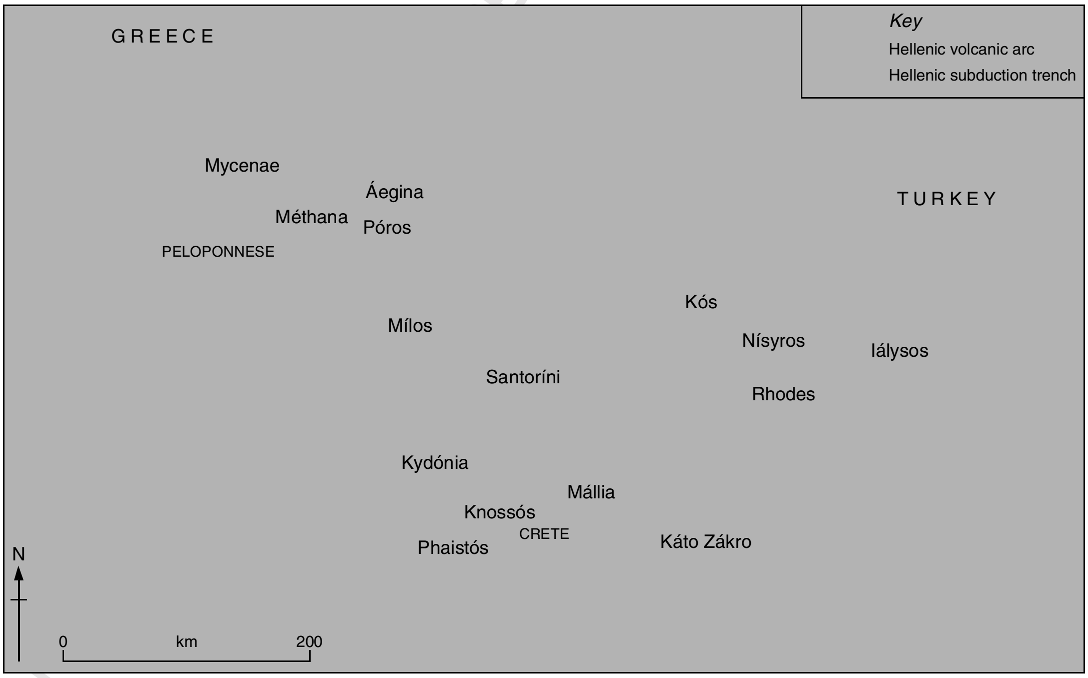
The volcanoes of Latium, or Lazio, stretch in a broad band, 100 km long, on the western margins of the Apennines and form the largest outcrop of volcanic rocks in Italy. Compared with Tuscany, the volcanoes are larger, more varied and more recent. They form distinct stratovolcanoes, calderas and vast sheets of **pumice**, as well as maars, domes and cinder cones. The eruptions are often associated with the formation of lakes such as Bolsena, Vico, Bracciano, Albano and Nemi, which embellish the rolling outlines of the Latium countryside. But the chief volcanic legacy in Latium is the series of hills dominating its skyline: the Monti Vulsini, Montefascione, Vico, Monti Cimini, Monti Sabatini to the north of Rome, and the Colli Albani (Alban Hills) to the south. For example, the Monti Vulsini were active from 400 000 to 60 000 years ago, the Monti Sabatini from 500 000 to 100 000 years ago, and the Colli Albani from 580 000 to 19 000 years ago. The eruptions produced rocks of a high potassic content and most are rich in **leucite**. **Leucitites**, phonolites and tephrites, are perhaps the most common, with smaller quantities of latites and trachytes.

The volcanoes of Campania are concentrated around the northern shores of the Bay of Naples, although Monte Vulture (in Basilicata) and Roccamonfina (on the border of southern Latium) also belong to this group. Like those in Latium, the Campanian volcanoes are associated with

3 Greece

The Hellenic volcanic arc is the best-developed island arc in Europe. It swings for 500 km across the southern Aegean Sea from the Isthmus of Corinth to Bodrum in Turkey. It comprises the smaller volcanic centres of Aegina, Póros and Méthana, and the larger accumulations of Mílos, Antíparos, Santoríni, Nísyros, Yalí and southwestern Kós. But only Méthana, Nísyros and Santoríni have recorded eruptions of more than fumaroles during historical times. However, the Minoan eruption of Santoríni in the Bronze Age was not only one of the greatest volcanic events in Europe during the past 10 000 years but it also made an most impressive contribution to one of its most spectacular landscapes.

The volcanic arc was generated by subduction of an oceanic part of the African plate beneath the small Aegean plate on the southern edge of the Eurasian plate. The volcanic arc rises some 220 km north of the Hellenic trench, where the upper surface of subducted slab has reached a



The Hellenic volcanic arc and the Minoan Aegean.

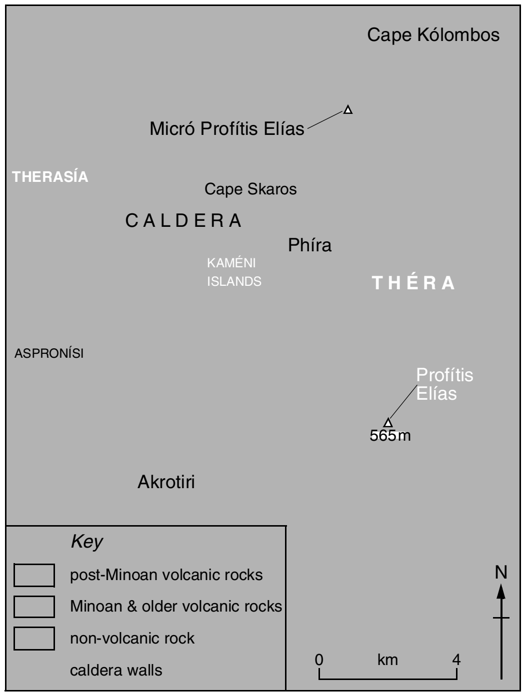
depth of 130–150 km (McKenzie 1972, Papadópoulos 1984, Huijsmans et al. 1988, Kalogerópoulos & Parítsis 1990). The oldest emerged rocks, on Mílos, are 3.5 million years old. During historical times, the Kaméni Islands in the Santoríni caldera have marked the most voluminous output from any centre in Greece. The Hellenic volcanoes have generally erupted calc-alkaline, andesitic, dacitic and rhyolitic rocks, and, among them, andesites and **dacites** each constitute about a third of the volcanic products ejected. Only Santoríni has expelled significant quantities of basalt.

In the west, the eruptions have been smaller and the lavas have usually been viscous. Thus, domes and thick flows of basaltic andesite and dacite, erupted about 1–2 million years ago, make up the hills in the central and southern two thirds of Aegina and the volcanic southern peninsula of Póros; and viscous flows also accumulated as low shields in western Mílos. However, greater magmatic differentiation, in relatively shallow reservoirs, in the centre and east of the arc occasionally generated more explosive eruptions of rhyodacitic and rhyolitic ash and pumice, and the collapse of calderas notably off southwestern Kós, in Nísyros and, of course, in Santoríni (Keller et al. 1990, Druitt & Francaviglia 1992, Druitt et al. 1999). Since the latest eruption in the arc took place in the Kaméni Islands in 1950, activity has been limited to mild fumaroles and hot springs that are manifest in all the volcanic centres, especially in Méthana, the Kaméni Islands and Nísyros.

SANTORÍNI

From a distance, Santoríni appears as a round island that rises to a broad central focus, with scattered white villages surrounded by vines and tomatoes in terraced fields of buff pumice. In the south, the rugged Cycladic limestones of Mount Profítis Elías form its highest point at 565 m. Santoríni is, in fact, a group of islands that acquired this name during the Venetian occupation, but, in classical times, it was called Théra, which is also often used today. However, it seems clearer to use Théra for the principal island and retain Santoríni for the whole group.

The glory of Santoríni is its sea-flooded caldera, about 85 km^2 in area, whose rim marks the formidable inner edge of three islands (Plate 6). On the main island, Théra, the northern part of the rim makes a rampart of red, brown and black layers of lava and cinders, 400 m high, but its southern part forms a less forbidding wall of buff pumice rising no more than 200 m. A similar wall faces it on the white pumice islet of Aspronísi (white island) to the west. Therasía, which has a rampart like northern Théra, then completes the circle. In the midst of the caldera, intermittent activity since 197 BC has formed the Kaméni (Burnt) Islands. They have been the site of all but



The generalized geology of Santoríni.

one of the eruptions of historical times in Santoríni, and they make a low, stark agglomeration of recent lava flows, domes and cones that offer a splendid views of the whole caldera.

The event that gave Santoríni its notoriety – and much of its spectacular landscape – was the Minoan eruption in the Bronze Age. The pumice ejected buried a city, excavated at Akrotíri, which had formed part of the Minoan civilization that was named after the legendary King Mínos, who reigned at the Palace of Knossós in Crete (Evans 1921–36). The Minoan eruption has also been blamed for the sudden end of this civilization (Marinátos 1939, Luce 1969, Doúmas 1978).

The growth of Santoríni

Before the present Hellenic volcanic arc ever existed, Mount Profítis Elías marked the summit of an island of limestones and schists that formed the most southerly of the Cycládes. It was at a depth of about 1000 m on the adjacent Aegean sea floor that eruptions began, perhaps as much as 3 million years ago. Santoríni apparently never formed a single stratovolcano, but separate vents erupted a complex volcanic field over a long period. The oldest volcanic rocks are exposed in the Akrotíri Peninsula on the southern arm of Théra, where, between 550 000 and 650 000 years ago or earlier, a dozen or so vents erupted dacitic domes, andesitic lava flows, spatter cones and cinder cones. Volcanic activity then shifted northeastwards and constructed the Peristeria volcano over 430 000 years ago, while emissions of andesitic and dacitic lavas built the *bases* of four shield volcanoes to a height of some 200 m: Megálo Vounó, Micró Profítis Elías, Therasía and Skáros (Pichler & Kussmaul 1980, Heiken & McCoy 1984, Huijsmans et al. 1988, Huijsmans & Barton 1990, Druitt et al. 1999). Events then occurred in two long cycles. The first cycle began 360 000 years ago and culminated 180 000 years ago in the powerful eruptions that expelled the rhyodacitic Lower Pumices. The second cycle lasted from 180 000 years ago until the rhyodacitic Plinian Minoan eruption in the Bronze Age. Large **silicic magma** reservoirs developed during the last 50 000 years of each cycle.

Santoríni had dozens of violent eruptions of rhyodacitic pumice during the second cycle. Many of these eruptions took place along two parallel fissure or fault systems, trending from northeast to southwest, one passing through Cape Kolómbos in the north; the other passing through the Kaméni Islands in the centre (Druitt & Francaviglia 1990, 1992).

The caldera of Santoríni was formed not all at once but seems to have resulted from four main episodes of collapse. After the Lower Pumices erupted about 180 000 years ago, a caldera collapsed and was probably flooded by the sea. Mainly andesitic eruptions then supervened and probably filled the caldera with both lava shields and layers of exploded fragments, such as the distinctive Middle Pumice and the Upper Scoria (Druitt et al. 1989, Huijsmans & Barton 1990). A second caldera then collapsed, chiefly in the north, about 70 000 years ago. Again, eruptions of basalts, andesites and rhyodacites filled the hollow and extended well beyond its walls. They developed the Skáros shield and the Therasía shield or dome complex.

About 21 000 years ago, both these lava piles were severely damaged when a rhyodacitic Plinian eruption brought about the collapse of the third caldera, centred on Cape Riva in northern Therasía (McClelland & Druitt 1989, Druitt et al. 1999). Subsequent eruptions then seem to have formed a volcanic island in the centre of this caldera, similar to the present Kaméni Islands.

Several millennia of quiescence allowed at least two (and perhaps many more) Minoan settlements to grow up on the island. One, near the southern tip of Therasía, was exposed when pumice was being quarried to make the dykes alongside the Suez Canal in 1869, but it has not yet been systematically excavated (Fouqué 1879). The main Minoan settlement yet discovered is being excavated at Akrotíri on the southern arm of Théra. It is possible that the fine naval-flotilla fresco unearthed there could depict the Minoan landscape of Santoríni, although its lack of perspective, not to mention its artistic licence, makes it hard to fit the details into a coherent picture. But, if the fresco is at all accurate, then a large body of water occupied central Santoríni, and the chief Minoan settlement on the island must have stood near the present southern tip of Therasía, and not at Akrotíri itself.

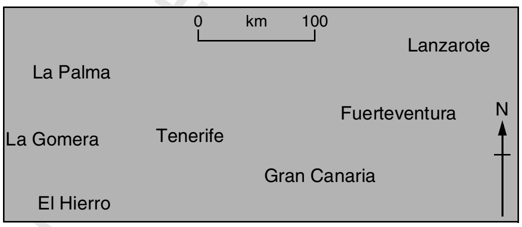
The Minoan eruption of Santoríni

The Minoan eruption was the largest on any European volcano in recent millennia and it destroyed the Minoan Bronze Age settlements on the island. As the magma pressure rose, the

PART 3 THE ATLANTIC

4 Spain: Canary Islands

he Canary Islands form Spanish provinces, situated off the Atlantic coast of Africa, between 1200 km and 1750 km southwest of Cádiz. The archipelago consists of seven main islands. Tenerife, covering 2058 km^2, is the largest, and El Hierro, only 275 km^2 in area, is the smallest, and Fuerteventura lies only 115 km from Africa. All the islands belong to the African plate. They fall into two groups. Fuerteventura and Lanzarote form the eastern group and belong to the same volcanotectonic unit that trends parallel to the African coast. Here the climate is arid, the vegetation is steppe like, and fissures have dominated the distribution of eruptions to such an extent that neither island has a marked scenic focus. In contrast, the central and western group of islands – El Hierro, La Palma, La Gomera, Tenerife, and Gran Canaria – are more mountainous. Thus, even little El Hierro reaches 1051 m and Tenerife rises to a majestic climax of 3715 m in the Pico de Teide. They lie in the path of the northeast trade winds, which bring cloud, humidity and a luxuriant vegetation to their northern windward shores, although their leeward southern slopes are often arid. Their lower parts enjoy an equable and mild climate throughout the year, and several have become some of Europe's major tourist attractions. Thus, in any season, the volcanologist is unlikely to be alone on the summit of Teide and may even encounter tourist-laden camels in Lanzarote. On the other hand, few areas beyond the shadow of Vesuvius have done more for popular appreciation of the impact of volcanism on mankind and the environment.



The Canary Islands.

The Canary Islands contain a great variety of volcanic forms that range from plateau basalts, which are the remains of large basal shields, to recent cinder cones and rugged lava flows that have often joined into malpaís; and their stratovolcanoes have sometimes been decapitated by large calderas. The islands have been considered as the type-locality of the caldera ever since Von Buch published his controversial work on their landforms in 1825. Indeed, the Caldera de las Cañadas in Tenerife is, with Santoríni, the most spectacular in all Europe. Fortunately, this well populated archipelago has not undergone a caldera-forming eruption in historical times.

The Canary Islands used to be inhabited by the Guancho peoples, who passed on some references to eruptions before they were exterminated by Spanish settlers. Lanzarote, Fuerteventura, La Gomera and El Hierro were settled from 1402, Gran Canaria from 1483, Tenerife from 1491, and La Palma finally from 1493. Thus, historical times in the archipelago amount to less than 600 years, during which activity has been dominated by basaltic eruptions along fissures, which occurred in Lanzarote, La Palma and Tenerife. In addition, parts of Fuerteventura, Gran Canaria and El Hierro all have cones and flows of such remarkable freshness that they scarcely seem to be more than a thousand years old.

Indeed, all the islands except La Gomera have had activity within the past 10 000 years. The recorded eruptions in the Canary Islands have occurred at average intervals of 30–35 years. The latest took place in La Palma in 1971, and by far the most prolonged and extensive historical eruption took place in Lanzarote from 1730 to 1736.

The volcanic activity in the archipelago is perhaps the most difficult to explain in all Europe. The islands lie on the passive continental margin of northwestern Africa, on one of the oldest parts of the Atlantic Ocean floor, where the basaltic oceanic crust ranges from 180 to 155 million years old from east to west (Araña & Carrecedo 1979). A basal complex outcrops on Fuerteventura, La Gomera and La Palma, and probably lies hidden beneath the remaining islands. It contains some sediments, some plutonic intrusions and some submarine basalts, but chiefly assemblies of dykes. However, most of the Canary Islands are much younger, and many parts of the surface are probably no more than a few thousand years old. The islands were born separately from different sources of magma and did not all develop in the same way. Thus, for instance, the oldest dated volcanic rocks occur in Fuerteventura, where they are about 20.6 million years old, but they are no more than 2.0 million years old in La Palma and about 1.12 million years old in El Hierro. The rocks themselves range from basalts to hawaiites, mugearites, phonolites and rhyolites. Basalts, chiefly emitted from fissures, account for the longest and most prolific eruptive episodes; and the more evolved rocks developed largely beneath the stratovolcanoes, probably in relatively shallow magma reservoirs (Valentin et al. 1990).

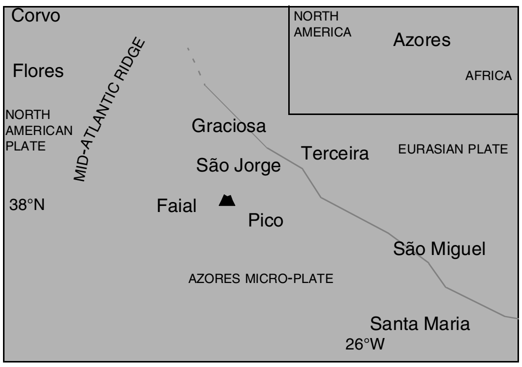
Tectonic movements might have played a role in the growth of the Canary Islands by opening up the oceanward prolongation of the South Atlas fault of North Africa (Anguita & Hernán 1975, Araña & Carracedo 1978). Nevertheless, the archipelago probably owes most of its growth to a hotspot, which has given rise to a broad westward development of activity in the islands (Carracedo 1994). It seems probable that masses from the rising magma have formed individual basal shields, and, at times, domed up their surface until major three-arm rift systems separated by angles of 120° have developed. The fissure systems on these rifts then enabled yet more magma to reach the surface; and they have, for example, become the zones of the most marked concentrations of recent emission centres in the islands. Thus, the rifts have been built up into large high ridges, which reach spectacular proportions in Tenerife, where they form a Y-shape pattern centred on Teide. These rift ridges grew up so quickly that they sometimes became unstable. Consequently, in El Hierro, La Palma and Tenerife, parts of these ridges have collapsed into the Atlantic Ocean in major landslides. Most of the eruptions in the Canary Islands during historical times have occurred on the fissures developed along these ridges. During these eruptions, fragments explode and form cones on the upper parts of the fissures, while fluid basalts, and perhaps spatter, emerge lower down. However, they have produced only tiny volumes of broadly alkaline basalts, and formed but small cones and thin lava flows.

5 Portugal: the Azores Islands

The Azores are an autonomous region of Portugal situated in the Atlantic Ocean 1500 km west of Lisbon. The archipelago of nine islands is scattered over 600 km and falls into three groups: Flores and Corvo in the west, Santa Maria and São Miguel in the east, and a central cluster of five islands – Terceira, Graciosa, São Jorge, Pico and Faial. Seven of the islands rise from the Azores Platform on the eastern flanks of the Mid-Atlantic Ridge. Only Flores and Corvo rise on its western flanks. All the islands are active except Santa Maria, which is the farthest from the Ridge. All except São Jorge have stratovolcanoes and all except one have been decapitated by calderas. The Pico do Pico, soaring to 2351 m above sea level, is the only stratovolcano that still retains the pristine glory that makes it the incomparable landmark of the Azores. Although the Azores are almost entirely volcanic, they are far from stark and bare: laurels, hydrangeas and azaleas dominate a floral extravaganza that is rarely seen in temperate climates.

The Azores were uninhabited when the Portuguese explorers were led to them by the goshawks, the *Açores*, that were flying about the islands. Settlement began first on Santa Maria and São Miguel in 1439 and then on Terceira in 1450, on Pico and Faial in 1466, on Graciosa and São Jorge in 1480, and on Flores and Corvo at the start of the next century. Historical records of eruptions therefore extend back only between 500 and 600 years, but over 30 eruptions have taken place during this period, either on the islands or off shore. However, the Azores are not growing rapidly; Iceland has a much higher output of lava per visible eruption (Self 1976); eruptions occur four times more often in Iceland (Ridley et al. 1974); and eruptions of similar composition have built the Canary Islands five to ten times faster (Moore 1991). But, of course, Iceland is 40 times larger than the Azores islands, and many submarine eruptions must have passed unnoticed on the Azores Platform.

The Azores and their submarine plinth grew up on the Mid-Atlantic Ridge near the triple junction of the North American, Eurasian and African plates. Their activity is probably related to a hotspot and perhaps also to a secondary band of seafloor spreading (McKenzie 1972, Laughton & Whitmarsh 1974, Weijermars 1987). The Mid-Atlantic Ridge, forming the boundary between the North American and Eurasian plates, passes through the Azores. The western islands of Flores and Corvo belong to the North American plate, but the location of the boundary between the Eurasian and African plates is not at all clear. The East Azores fracture zone runs from the Mid-Atlantic Ridge along the southern edge of the Azores Platform. Thus, if the fracture zone



The Azores and the Mid-Atlantic Ridge.

forms the main plate boundary, then the central and eastern Azores must belong to the Eurasian plate. However, an axis of secondary seafloor spreading runs through the central Azores along the Terceira Rift, which probably passes through Graciosa, Terceira and São Miguel (Krause & Watkins 1970, Self 1976, Searle 1980). In either case, parts of the central and eastern Azores could therefore belong to the African plate or to an Azores microplate. The volcanic activity in the Azores was most probably also intensified by one large, or several small, hotspot plumes (Féraud et al. 1980). Whatever the reasons behind the growth of the central and eastern Azores, all display a common and impressive predominance of stratovolcanoes, rifts, faults, fissures and volcanic alignments, running parallel to the spreading axis, that have been the leitmotifs in the development of their scenery.

The stratovolcanoes in the Azores are mostly gently sloping cones, usually more than 10 km in diameter and rising about 1000 m above sea level. They are crowned by beautiful deep calderas, which so impressed the early settlers that they also rather confusingly gave the name Caldeira (cauldron) to the whole mountain. These calderas are the hallmarks of the Azores.

The eruptions that have taken place along fissures running from northwest to southeast are the second most striking characteristic of the Azores and they completely dominate the landscape of São Jorge. What these eruptions lack in volume they make up for in number, for there are over a thousand cinder cones in the Azores. They occur on the flanks of stratovolcanoes and dominate the scenery on the plains and plateaux, and they are commonly associated with basaltic, hawaiitic or sometimes mugearitic lava flows. The younger flows often have rugged black aa surfaces, which the early settlers called mistérios, because they had frightening and mysterious associations that the eruptions during historical times did nothing to dispel. Although they have now often been planted with woodlands, they still stand out among the meadowlands of the Azores, and they reach their finest expression on Pico.

The fissure eruptions in the Azores extend well below sea level. Deeper eruptions, stifled by the water pressure, reached the surface as bubbling gas emissions and hot discoloured seas. Such eruptions have marked the activity of the Don João de Castro Bank. But, in the shallower coastal waters, Surtseyan eruptions built bulky tuff cones such as those protecting both Angra do Heroísmo in Terceira, and Horta in Faial. Older Surtseyan tuff cones are dotted about the coasts of the Azores, but, because they formed in such vulnerable positions, marine erosion soon reduced them to picturesque islets such as the Ilhéus das Cabras, off Terceira, and the Ilhéus dos Mosteiros off São Miguel.

Several islands have been marked by faulting and rifting, which was probably associated with the zone of secondary spreading branching from the Mid-Atlantic Ridge. The Terceira Rift transects that island and São Miguel, and another rift in eastern Faial forms a distinct fault trough. On the other hand, uplifted blocks seem to delimit most of both São Jorge and eastern Pico. The archipelago still suffers from typical mid-ocean-ridge earthquakes that are less than magnitude 5.0 on the Richter scale and have shallow epicentres, less than 30 km deep.

Although six of the islands are still active, fumaroles are their only persistent manifestation. They make their best displays in the Caldeira das Furnas in São Miguel, where tourists can bathe or have meals specially cooked – in different vents, of course. Weak fumes usually issue from the summit of Pico, and the earthquake in May 1958 briefly revived those in the caldera of Faial. Magmatic emissions are much less frequent; the latest formed Capelinhos in Faial in 1957–8, although other eruptions have since occurred below sea level. At all events, volcanic features are never out of sight in the Azores, and volcanic activity plays a role in the local place names exceeded only by religion. Mistério and caldeira have already been mentioned, but other common names include biscoitos (rugged aa lava flow), bagacina (cinders), queimado (burnt), fogo (fire), furna (oven), timão (arched yoke) and cabeço (head). Thus, volcanic activity is never far from the consciousness of the Azoreans.

The Azores are young. The eastern group contains the oldest rocks, which reach about 5 million years old in Santa Maria and 4 million years old in eastern São Miguel (Abdel-Monem et al. 1975). No lavas on any of the remaining islands are apparently more than a million years old. The oldest rocks commonly outcrop in the southeast of each island, and the more recent eruptions have tended to occur in the northwest, nearest the Mid-Atlantic Ridge. Nevertheless, there was no regular progression of eruptions from island to island towards this ridge. Thus, for instance, Faial, in the west, and São Miguel, in the east:

both have some of the oldest and some of the youngest lavas in the archipelago (Booth & Croasdale 1978).

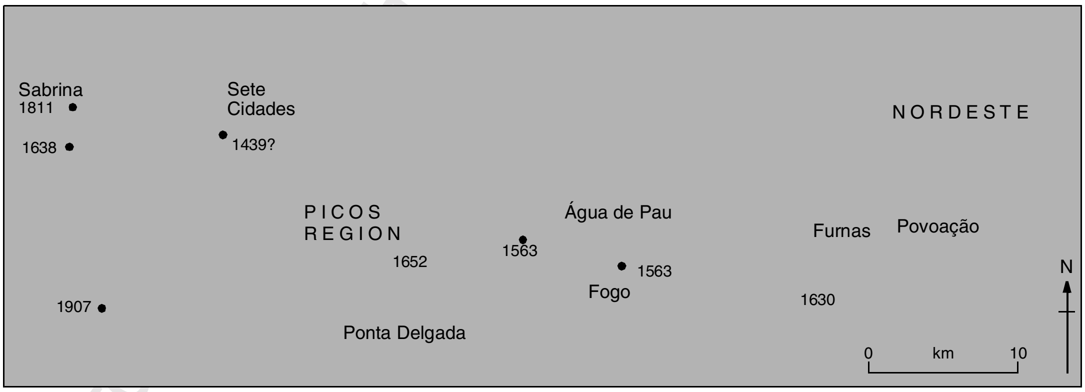
The eruptions in the Azores produced a predominance of alkali basalts, hawaiites and mugearites, but some evolution to trachytes and pantellerites was associated with the violent explosions that formed the calderas. The basaltic rocks, commonly erupted from fissures, formed many cinder cones and lava flows, and Surtseyan eruptions took place where these fissures extended into shallow water.

SÃO MIGUEL

São Miguel is the largest and most varied island in the Azores. It covers an area of 747 km^2 and is 65 km long, with a maximum width of 15 km, culminating at a peak of 1103 m at the Pico da Vara. It is notable for its rich vegetation, fertile soils, four stratovolcanoes with majestic calderas, dozens of cinder cones, aligned for the most part on fissures, thermal springs, and a beautiful coastline dominated in many places by high cliffs. However, large tracts of bare lava are rare, for most of the flows are either weathered or have been blanketed by trachytic pumice exploded from the stratovolcanoes.

The eruptions that gave rise to São Miguel began about 4 million years ago at a depth of 2000 m on the floor of the Atlantic Ocean, and the island has some of the oldest exposed lavas in the archipelago. However, five eruptions on land, and a further seven offshore, have been recorded since the island was first settled in 1439 (Canto 1880b, Weston 1964, Mitchell-Thomé 1981). In general, activity on São Miguel spread westwards and has now probably ceased in the east.

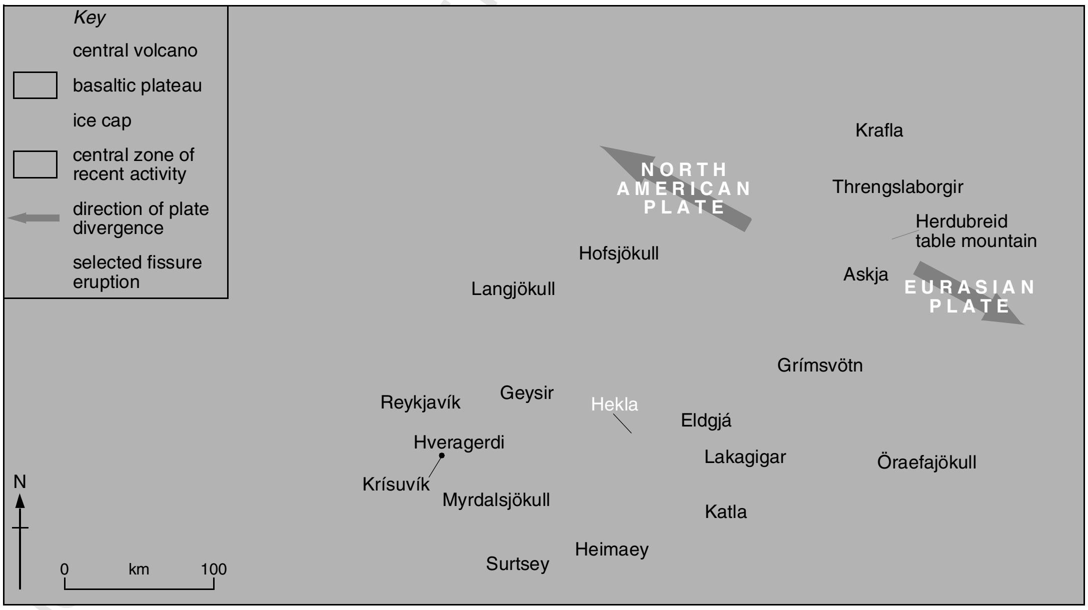
Four stratovolcanoes form the backbone of the island. Povoação and Furnas are contiguous in the east; the Água de Pau, or Fogo volcano, occupies the centre; and the Sete Cidades volcano forms much of the northwestern part of the island. Sete Cidades was a separate island until it was joined to the rest of São Miguel by the eruptions of the Região dos Picos (Booth et al. 1978).



The calderas and the recent eruptions on and around São Miguel.

6 Iceland

Iceland covers an area of 102 846 km^2 and it is almost completely volcanic in origin. It constitutes the longest emerged segment along any of the world's mid-ocean ridges and it is the largest volcanic area in Europe. The landscape of Iceland offers a glimpse of how mid-ocean ridges develop, especially in the central axial zone of contemporary activity, which curves across the island from north to southwest in a swathe 60–80 km wide. Here, the North American plate on the west is diverging from the Eurasian plate on the east. Crustal accretion occurs at their edges through the injection of great swarms of sheeted dykes, often accompanied by eruptions of basalts onto the land surface. Broad expanses of plateaux basalts stretch from both sides of the band of contemporary activity and cover three quarters of Iceland, which were themselves erupted on older axial zones during the past 16 million years, but have been carried to extinction away from the axis, as crustal divergence, rifting and accretion have continued. Thus, in northwest Iceland, the exposed basalts are about 15 million years old, whereas those in eastern Iceland date from 13 million years ago (Saemundsson 1986). They are bordered on their inner



The main volcanic features of Iceland, with the central zone of recent volcanic activity between the diverging Eurasian and North American plates.

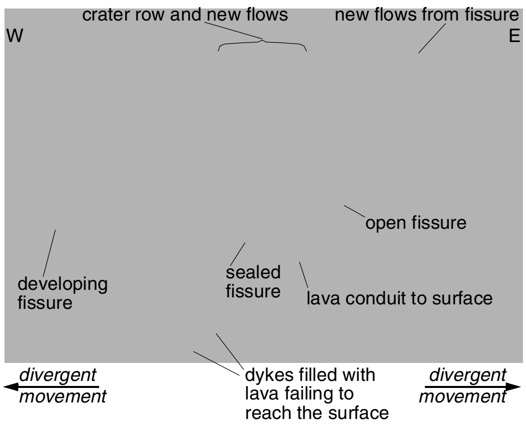
edges, alongside the band of present activity, by younger basalts 3.1–0.7 million years old. In the zone of contemporary activity, all the eruptions occurred less than 700 000 years ago. All of these basalts erupted in a broadly similar fashion and, therefore, the activity of the contemporary axial zone clearly indicates how most of Iceland was formed. Iceland has widened by some 400 km from east to west since the divergence began. The axial zone is widening at an average rate of 1.5–2.0 cm per year (Tryggvason 1984).

Iceland has been built up on a segment of the Mid-Atlantic Ridge, which lies between the Kolbeinsey Ridge to the north and the Reykjanes Ridge to the southwest. The 400 km-long Icelandic segment is offset by two transform-fracture zones where most of the major earthquakes have occurred in historical times: the Tjörnes fracture zone off the north coast and the south Iceland seismic zone crossing southwestern Iceland (Saemundsson 1979, 1986).

These tectonic aspects of Iceland are fundamentally similar to those displayed on submarine spreading ridges. Nevertheless, Iceland represents an unusual volume of volcanic materials – more than twice the thickness of the average ridge – built above sea level by the presence of a hotspot beneath the spreading axis, which has been active for at least 25 million years and perhaps as much as 44 million years (Sigurdsson & Loebner 1981). Volcanic rocks about 1500 m thick are exposed in Iceland and they lie on a volcanic basement three times thicker (Saemundsson 1979). The Icelandic hotspot seems to be a cylindrical zone about 300–400 km in diameter and more than 400 km deep (Wolfe et al. 1997). It is probably now centred beneath the zone of maximum lava accumulation that lies below the highest parts of the axial zone under Vatnajökull (Saemundsson 1986).

Of the exposed volcanic sequences, basalts represent 80–85 per cent, silicic and intermediate materials about 10 per cent, and the remainder comprises fluvial or glacial sediments that are themselves derived from volcanic rocks. The basalts form distinct petrological and morphological units. Porphyritic basalts arise most often in large rapid eruptions from fissures and they form characteristically massive lava flows. Olivine-rich tholeiitic basalts are emitted as thin individual pahoehoe flows (called helluhraun in Iceland), which repeated eruptions often pile up in lava shields. They seem to come from magmas lying more than 10 km deep. On the other hand, olivine-poor tholeiitic basalts emerge chiefly from fissures and the central volcanoes, after having spent time in shallow reservoirs. They form as aa lava flows (called apalhraun in Iceland) Alkali olivine basalts erupt from reservoirs about 3 km deep outside the main zones of rifting, and tended to develop after, and cover the products of, the tholeiitic activity. The greatest differentiation, probably derived after the longest periods in shallow reservoirs, is represented by the silicic eruptions, which are often associated with violent explosions that have reached Plinian proportions at Hekla, Askja and Öraefajökull. Among the more silicic rocks, about two thirds form lava flows or intrusions, but one third comprises layers of welded tuffs and ash that are often of a rhyolitic or rhyodacitic nature. Hekla, Öraefajökull and Askja have been their main sources in historical times.

Many of the characteristic genetic, tectonic and petrological features of the mid-ocean ridges imparted to Iceland can be studied in the open-air landscape, without recourse to the expensive equipment required where the ridges remain submerged. However, high precipitation and proximity to the Arctic Circle have helped maintain four main ice caps. Vatnajökull, with an area of 8400 km^2, is the largest ice sheet in Europe. The smaller ice caps of Langjökull, Mýrdalsjökull and Hofsjökull together are about 2500 km^2 in area. They create additional problems when eruptions take place beneath them, for they often generate destructive **jökulhlaup**s or glacier bursts. Much of the rest of the country lies in a periglacial subpolar climatic environment, where the general absence of vegetation



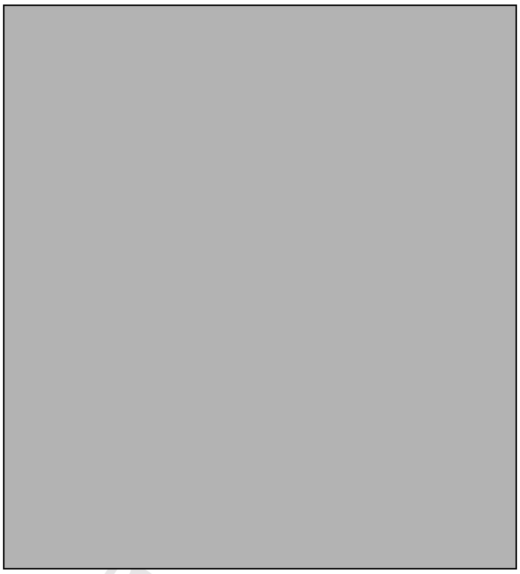
A typical Icelandic rift and fissure swarm (after Imsland 1989).

and thick soils reveals the eruptive features with a stark clarity that makes Iceland one of the finest volcanic exhibitions on Earth. Moreover, for a mid-ocean ridge environment, the volcanic landforms display a surprising variety and, although basaltic effusions have been predominant, almost every kind of volcano can be found (Thórarinsson & Saemundsson 1979). Volcanic systems composed of an elongated fissure swarm, with a central volcano in its midst that might even have developed a caldera, are some of the most striking elements of contemporary activity (Jakobsson 1979). They are accompanied by broad basaltic shields, much steeper table mountains formed beneath the old ice sheets, occasional domes of silicic lava, as well as maars and tuff rings, and a whole gamut of hydrothermal features.

The Norse settlement of Iceland began in AD 874 and thus historical records of volcanic activity, however vague or conflicting in the early centuries, are available for more than a thousand years. On average, a magmatic eruption is under way in Iceland every fifth year (Thórarinsson 1981). However, most **Icelandic eruptions** are among the least dangerous in the volcanic repertoire, although they are often of great scientific interest. The formation of Surtsey in 1963 not only created a new island in the Vestmannaeyar but also did much to clarify ideas about these particular Surtseyan eruptions. The eruption on the neighbouring island of Heimaey ten years later marked an important step in the development of procedures for civil protection and damage limitation. Finally, the studies of the rifting and eruptive episode that began at Krafla volcano in 1975 gave greater insights into the way that active mid-ocean ridges operate.

The plateau basalts

The plateau basalts cover about three quarters of Iceland, forming open and rather stark uplands of rounded hills and ridges, between 750 m and 1250 m high, each scarred by the outcrops of layered lava flows. They have been scraped bare by repeated glaciations, and eroded by streams in the non-glacial periods. The lava flows now dip gently down towards the axial zone from both west and east (Saemundsson 1986). Most of the plateaux developed from eruptions of tholeiitic basalts that emerged from deep fissures as widespreading fluid lava flows, 5–15 m thick. Central vent volcanoes may also amount to as much as



ANTHONY NEWTON

Piles of lava flows forming craggy escarpments in the Icelandic plateau basalts, Reykjarfjördur.

half of the volume of the plateaux, although they have often been buried by later lava flows (Walker 1963). There are perhaps as many as 50 or more such central volcanoes. They mainly form shields and occasional stratovolcanoes composed chiefly of basalts, but also have some andesites or even rhyolites in their make up. They have gentle slopes and modest heights. Breiddalur, in eastern Iceland, for instance, had a volume of 400 km^3 and gentle slopes of 9°, but it probably never stood more than 600 m above the surrounding lava plains. As they grew, the central volcanoes were periodically swamped by thicker and more fluid flood basalts disgorged from the fissures around them, so that they now form insignificant features in the landscape.

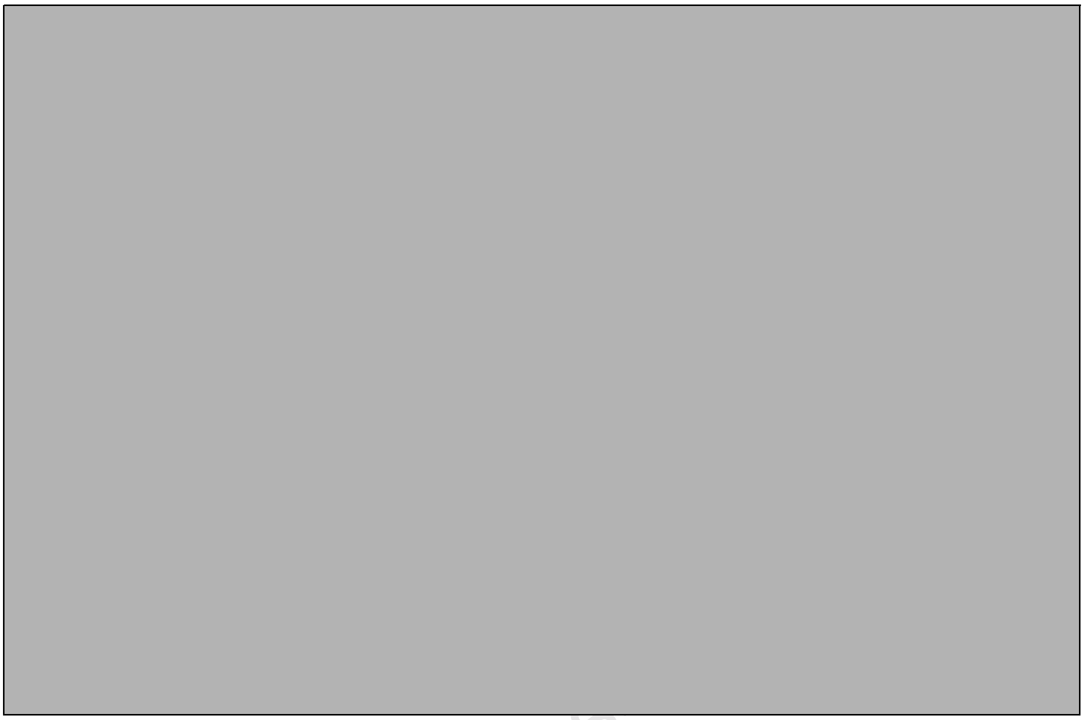
An essentially similar pattern of eruptions continued within the more recent series, initiated 3.1 million years ago, that covers a quarter of Iceland along each side of the active zone and is more than 500 m thick. Glaciations introduced greater variety, not only by depositing glacial debris between the lavas but more importantly by provoking the formation of pillow lavas, pillow breccias and **palagonites** during **subglacial eruptions**. These palagonites are known as móberg in Iceland.

7 Jan Mayen

he lonely Norwegian island of Jan Mayen lies 650 km northeast of Iceland in the North Atlantic Ocean at 71°N and 8°W. It is wholly volcanic in origin, covers an area of 320 km^2, runs 54 km from northeast to southwest, and is mostly less than 10 km wide. Historical records extend back about 400 years, but they are incomplete and scanty, for this grim, cold, isolated, inhospitable and often icebound island has supported settlement only rarely, and it now acts as a weather and navigation station. The island has two distinct parts, each about 25 km long, that are offset from each other by an isthmus. Both are dominated by fissures trending from northeast to southwest (Noe-Nygaard 1974). The narrow southwestern area, Sör-Jan, is a hilly range rising to 750 m above sea level, where fissure eruptions have formed a series of aligned trachytic domes and many cinder cones, from which recent lava flows have spread down to the coast. The northeastern part of the island, Nord-Jan, is wider, higher and more spectacular, for it is dominated by the basaltic stratovolcano, Beerenberg, the northernmost active volcano on land in the world. Beerenberg rises from 3000 m below sea level to 2277 m above sea level, its summit crowned by an ice cap that radiates glaciers down towards the coast. The central crater, Sentralkrateret, more than 1 km across and 300 m deep, feeds the most powerful of these glaciers, Weyprechtbreen. Beerenberg is often shrouded in fog or storm clouds, but in clear interludes the glistening ice and snow form a stunning contrast with the ice-free areas, which are often covered by fresh black and red cinder cones and lava flows erupted from fissures on its flanks (Fitch 1964, Sylvester 1975, Imsland 1978). In spite of the presence of the great stratovolcano, it is the fissure eruptions that have dictated the relief and outline of Jan Mayen, and even Beerenberg itself is aligned in the predominant northeast to southwest direction. The same trends are also followed by the volcanic Stimen bank, 15 km long and less than 100 m deep, in the ocean southwest of Sör-Jan. The form of Jan Mayen is thus closely related to major regional tectonic features.

Jan Mayen lies near a major offset of the Mid-Atlantic Ridge. The Kolbeinsey Ridge forms its main mid-ocean spine stretching 650 km north-northeastwards from Iceland. It is then offset 200 km to the east before resuming its course towards Spitzbergen as the Mohns Ridge. The line of the offset is marked by the Jan Mayen fracture zone, generated by a sheer displacement that forms a continuous linear depression more than 2000 m deep across the ocean floor (Saemundsson 1986). Jan Mayen rises where the fracture zone joins the Mohns Ridge, where enough lava could reach the surface to build up an island (Havskov & Atakan 1991). However, the tectonic situation of Jan Mayen is more complex than this basic background to its volcanic activity would, perhaps, imply (Johnson & Heezen 1967). It may also have grown up above a hotspot, probably now centred beneath the Eggvin bank, 150 km west of Jan Mayen, near the northern end of the Kolbeinsey Ridge.

From the scarce evidence available, eruptions on Jan Mayen seem to be separated by about a century of rest. Although eruption rates could have been higher in the past, the rate of volcanic activity in historic time has been low in Jan Mayen, and the average eruption has produced only about 0.07 km^3 of lava. Some 5.35 km^3 of



PALL IMSLAND

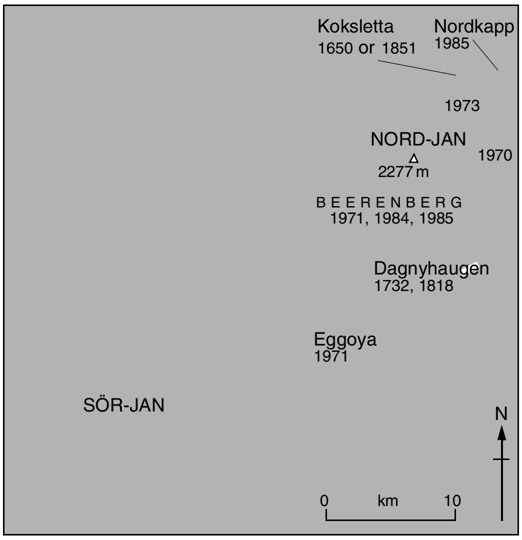
January 7 1985, the second day of an eruption on the northern flanks of Beerenberg, the eruption column turning towards the east.

lava has erupted altogether during the past 10 000 years or so (Imsland 1978).

Many of the Jan Mayen lavas are alkali-olivine basalts of relatively high potash content. **Ankaramites** and magnesium-rich basalts are common on Beerenberg; more evolved basalts, associated with trachytes, are more characteristic of Sör-Jan (Imsland 1986). Sör-Jan is the oldest part of Jan Mayen, forming a range of aligned cinder cones and lava flows composed of ankaramitic basalts accompanied by several trachytic domes. Volcanic activity may have begun in the southwest and shifted northeastwards (Wordie 1922, 1926).

Beerenberg clearly represents the modern volcanic climax in Jan Mayen. The rocks are predominantly alkali-olivine basalts. Beerenberg grew up in four distinct phases, each of which is reflected in its morphological characteristics. Little is known about the first – submarine and longest – phase in its growth. It undoubtedly expelled the most lava, for the plinth on which the volcano stands extends southwestwards beneath the rest of Jan Mayen and probably includes some of the Jan Mayen Ridge as well. This submarine activity continued in a northeasterly direction until a phase of vigorous Surtseyan eruptions, now represented by basal tuffs, heralded the emergence of the island about 500 000 years ago (Fitch et al. 1965, Imsland 1978).

The second phase of activity formed the broad basal shield of Beerenberg, which has a diameter at sea level of 15–24 km. It is now represented by the various layers of the Kapp Muyen group, where the ankaramitic lavas lie between various glacial beds (Fitch 1964). This second phase had three unequal parts. At first, basaltic emissions from a central vent gradually built up the shield to a height of about 750 m. It was interrupted by an explosive episode that expelled the Havhestberget formation, an ashflow of basaltic pumice that was directed mainly to the southwest, where it now covers glaciated older lavas in a wide plateau leading towards Sör-Jan. The last episode marked a return to effusive conditions that built the rest of the basal shield. Innumerable fluid flows of ankaramitic basalts, usually less than 20 m thick, radiated from the central vent, and together they compose the Nordvestkapp formation (Fitch 1964). This is the most voluminous formation in the whole of Beerenberg, and the hub of the shield eventually rose to a height of about 1500 m. When these eruptions waned,



Historical eruptions on Jan Mayen.

erosion then carved valleys into the flanks of the shield.

The renewal of volcanic activity in the third phase was marked by a significant change. More viscous hawaiites and mugearites rapidly formed the steep-sided lava cone, about 750 m high and 5 km across, that lies like an enormous sand-castle on top of the basal shield. The formation of the main cone of the stratovolcano and its chief crater, Sentralkrateret, was probably completed about 6000–7000 years ago (Fitch 1964). Then followed a period of fluvial, glacial and marine erosion forming barrancos, small high-level glacial corries and steep cliffs. It was probably at the end of this third phase that displacements formed the great fault cliff that bounds the north-eastern flanks of Beerenberg.

The fourth and latest phase of activity on Beerenberg during the past 6000 years or so has been dominated on its outer flanks by fissure eruptions that created several small cinder cones and widespread lava flows. These fissures trend along the axis of Jan Mayen and curve through the central cone of Beerenberg. The sequence of events has been established in relation to marine platforms around the perimeter of the strato-volcano. About 4000–5000 years ago, the chief fissure eruptions formed the Tromosryggen Ridge of cinder cones and flows, which is 300 m high and 6 km long. The lavas cascaded down the newly formed fault cliff on the northeastern end of Beerenberg and extended in lava deltas at its foot. These features were subsequently eroded by glaciers and cliffed by the waves. A similar episode of fissure eruptions later gave rise both to the Sarskrateret cone, in the far northeast of the island, and to the Koksletta lavas in the north. These lavas flowed down cliffs that had already been carved into the Tromosryggen basalts; they spread out into a broad platform, 4 km long and 1 km wide, at the northern tip of Jan Mayen. They may have erupted 2500–3500 years ago (Fitch 1964). On the other hand, they are so remarkably unweathered that they could have erupted even as recently as 1820–82. For example, the Koksletta lava platform was mapped in 1882, but it was not marked on Scoresby's quite accurate map in 1820, perhaps for the good reason that it did not then exist (Sylvester 1975). It has been suggested that the Koksletta eruption could have taken place in 1851 (Havskov & Atakan 1991).

This fourth phase of eruptions has certainly continued into historical times, but, even then, isolation, frequent low cloud and the long spells without permanent settlement have combined to make observations of eruptions unreliable, intermittent and scanty. No activity appears to have taken place in Sör-Jan. On Beerenberg, an eruption may have occurred at Koksletta in 1650, but any resulting forms have not been identified. But the results of the more reliably dated eruptions in 1732 and 1818 can be seen in the fresh unglaciated lavas and cones at Dagnyhaugen, low on the southwestern flanks of Beerenberg. The opposite northeastern flanks, near the Nordkapp, probably saw activity about 1850, and certainly in 1970, 1971, 1973 and 1985

The eruption in January 1985

Several strong earthquakes approaching magnitude 5.0 on the Richter scale shook the island on 4–6 January 1985. The eruption began in the afternoon of 6 January, and lasted some 35–40 hours before it ended on 8 January. It occurred on a small fissure, 1 km long, at the far northeastern corner of Jan Mayen, extending from sea level up to 200 m on the north side of the Sarskrateret cone. Three main craters emitted gas and spatter, and the wind distributed fine ash from a dark-brown column that rose 1 km above the vents. About 7 million m^3 of volcanic material (about one tenth of an average Jan Mayen eruption) was given out. Lavas also gushed vigorously out northwards into the sea and eventually added about 0.25 km^2 to the land area of Jan Mayen.

PART 4 NORTHERN EUROPE

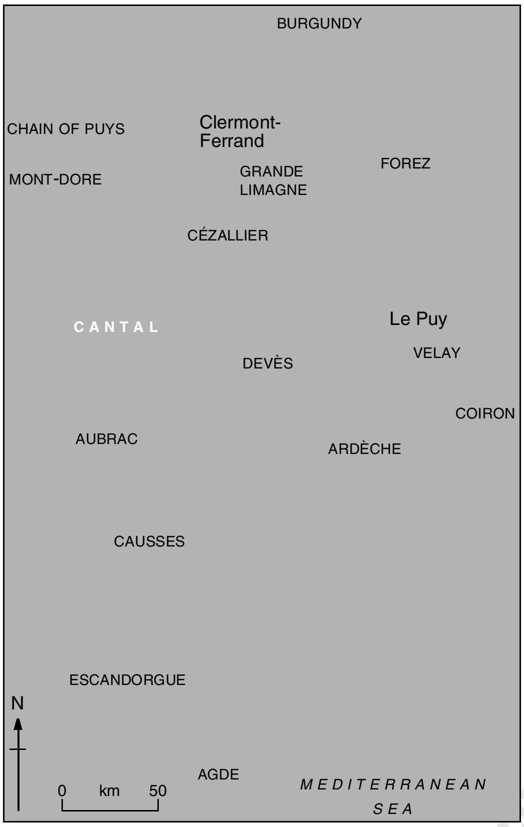
8 France

o volcano has erupted in France in historical times, but prehistoric peoples almost certainly witnessed some of its latest activity. The most recent act in several million years of eruptions occurred about 6000 years ago when the crater now occupied by Lac Pavin exploded in Auvergne and further eruptions could occur in that province.

During the past 10 million years, eruptions have been concentrated in the Massif Central, and volcanic landforms of great variety dominate the scenery of Auvergne and Velay, in the centre and southeast of this vast upland. Thus, the Chain of Puys has scores of cinder cones and lava flows, with a few majestic domes; the Mont-Dore and Cantal massifs are stratovolcanoes forming the highest peaks in the centre of the region; the Cézallier, Aubrac and Devès all form widespread basaltic plateaux. In Velay, lava plateaux predominate in the west and the extruded sucs in the east. More sporadic activity also occurred in Burgundy and Forez in the north, in Ardèche in the southeast, and in a zone stretching across the Causses to the Escandorgue Chain in Languedoc. There are volcanic lakes everywhere, such as Lac d’Aydat, which have been impounded by lava flows, and maars formed by explosions, such as the Gour de Tazenat and the Lac du Bouchet. Older lava masses have been set in relief by the removal of weaker sediments around them. In the Velay and in the Grande Limagne, erosion has reduced old flows and vents to ridges, buttes or necks that protect ancient villages or form the plinths of monuments that make Le Puy-en-Velay, for instance, one of the most spectacular towns in France. The plateau formed by an ancient lava lake at Gergovie made an ideal site for a Gaullish defensive site; nearby, the Montagne de la Serre points its lava-capped ridge into the Grande Limagne; and, in the far southeast, the Coiron lavas protected a spur like a great paw that juts out from the Massif Central to threaten the Rhône Valley (e.g. Scarth 1967, Bout 1973, Peterlongo 1978, Gèze 1979, Rouire & Rousset 1980, de Goër de Hervé et al. 1991).

However, volcanic activity was not relayed in any regular pattern from one area to another and, for example, some of the oldest and youngest volcanic features in the Massif Central are both found within sight of the Puy de Dôme. The volcanoes all lie upon a basement of faulted blocks and troughs, which are separated by pronounced escarpments. Most of the faulting took place before the eruptions began. But, erosion has incised the area markedly during the past 2 or 3 million years, and streams eroded deep into the volcanoes, both as they grew up and after they became extinct: the central core of Mont-Dore was gutted and deep gorges radiated from the Cantal stratovolcano. They developed a labyrinthine stratigraphy that can be deciphered only by the most sophisticated of modern techniques (Cantagrel & Baubron 1983). The most recent theatre of activity in the area is the Chain of Puys, whose fresh and clearcut features culminate in one of the most distinctive mountains in all of France, the Puy de Dôme.

The eruptive climaxes of the various areas of activity began with the Cantal, and the Aubrac and Cézallier plateaux, between 9 and 7 million years ago. They continued with those in Velay from about 8 to 6 million years ago. The climax of the Mont-Dore occurred about 3 million years



Volcanic areas of France

ago, but eruptions continued until about 250 000 years ago. The Devès plateau erupted mainly about 2 million years ago, but the apogee of the Chain of Puys took place only around 10 000 years ago. However, the intervals of repose were undoubtedly much longer than the eruptive acts. Thus, the total number of active years was small in comparison to the millions of years encompassed by the whole eruptive sequence.

Most of the lavas erupted in the Massif Central are basanites and alkaline basalts. They occur in the older eruptions but are also very common in the planèzes of Mont-Dore and the Cantal, as well as the lava plateaux of Aubrac and the Cézallier. More differentiated lavas form hawaiites (here called labradorites or trachybasalts), mugearites (called doreites and ordanchites, for instance, in the Mont-Dore), and benmoreites (known as sancyites in the Mont-Dore). In the local terminology, too, the doreites and sancyites were grouped together as "trachyandesites", in both the Mont-Dore and the Cantal (Peterlongo 1978). Trachytes developed from alkaline basalts in the Chain of Puys, rhyolites eventually developed in the Mont-Dore, and trachyrhyolites in the Cantal to form domes and pumice ashflows. Phonolites also developed widely in Velay and from small secondary reservoirs in Mont-Dore.

Aligned vents have produced by far the most numerous and widespread eruptions in the Massif Central. The vast majority are related to fissures, but the major faults have permitted the ascent of magma only very rarely. Thus, for example, in the area near Clermont-Ferrand that is riddled by hundreds of vents, the major faults forming the border between the Grande Limagne and the plinth of the Chain of Puys have produced only two volcanoes (Scarth 1966). Most of the fractures and fissures trend from north to south, northwest to southeast, or north-northeast to south-southwest. An important feature of the alignments is that eruptions occurred upon them from time to time, but not all at once, such as on the fissures in Iceland.

Closely spaced eruptions along such fissures gave rise to the major basaltic plateaux of the Massif Central. The Cézallier, Aubrac, Devès and Coiron plateaux all trend from northwest to southeast, and their lavas show differentiation towards hawaiites and mugearites. These lavas often emerged in such quantities that they swamped the previous relief. But in Devès, in particular, the fissures have not only formed lava flows but also many maars, and line after line of cinder cones, known as gardes. Aligned volcanic activity reached its climax in eastern Velay and especially in the Chain of Puys, where not only basaltic but also more evolved magmas erupted. Thus, in eastern Velay, viscous phonolitic extrusions formed the steep-sided sucs that rise above the basalts; and, in the centre of the Chain of Puys, trachytic domes dominate the scenery among the lines of cinder cones.

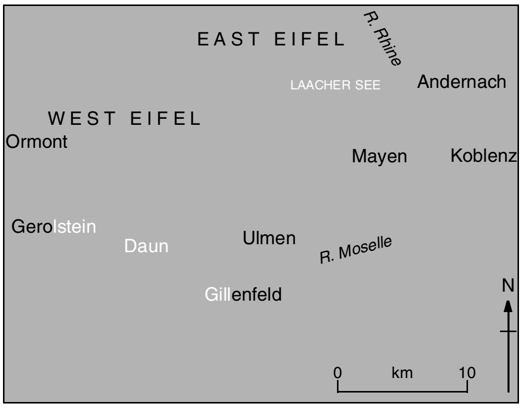
The centrally clustered vents of the Massif Central form the smallest category of volcanic features, but also two of its most prominent landforms: the stratovolcanoes of the Mont-Dore and Cantal. However, much smaller stratovolcanoes have been all but hidden in the Boutières of eastern Velay and the Luguet in the Cézallier plateau. These stratovolcanoes developed after an initial phase of more scattered basaltic eruptions. The spatial concentration was associated with magma evolution towards mugearites and benmoreites (here the "trachyandesitic" doreites and sancyites), followed on the one hand by trachytes and phonolites and on the other by less common

9 Germany

he volcanic eruptions in Germany were concentrated in a belt, about 600 km long, following the valley of the River Rhine, which occurred when a rift developed across Europe as the Atlantic Ocean opened. Most of the eruptions took place along major faults trending mainly from north to south or sometimes from northwest to southeast. Successive episodes of rifting were reflected in the activity that reached its climax in areas such as the Odenwald, Spessart, Taunus and Westerwald, Swabia and the Kaiserstuhl more than 15 million years ago.

It was only after a long interval that eruptions resumed in the Eifel Massif, which forms an extensive plateau, about 500 m high, in the area between the River Rhine and its tributary the River Moselle. The West Eifel zone, near Daun, runs for 50 km from northwest to southeast in a band 20 km wide. The East Eifel zone, centred on the Laacher See, near Mayen, is an area with some 50 vents that stretches 35 km from the River Rhine in a belt about 25 km broad. The West Eifel massif has long been famous for its maars, the circular lakes reaching up to more than 2 km in diameter, for which the region has become the type locality. But these beautiful relics of hydrovolcanic eruptions are also accompanied by tuff rings and many cinder cones, lava flows and domes, as well as extensive blankets of pumice. The younger flows, cinders and pumice have been widely quarried, whereas the older materials have weathered to provide a mixture of rich arable and meadow lands and woods surrounding prosperous rural towns.

Volcanic activity began in the Eifel region about 800 000 years ago and reached its distinct late climax between about 12 000 and 10 000 years ago. It was also some 11 000 years ago that the great eruptions of Laacher See distributed indicator beds as far afield as Switzerland, northern Italy and southern Sweden (Bogaard & Schmincke 1985). One or perhaps two magma reservoirs erupted alkaline basalts, basanites, tephrites, phonolites and some trachytes. Basalts, tephrites and basanites were responsible for most of the lava flows, cinder cones, maars and tuff rings, whereas the domes and most of the layers of pumice are chiefly phonolitic. Some domes and layers of tuff are also composed of selbergite, a local phonolite rich in leucite. Although the region has been quiet for several thousand years, emissions of carbon dioxide from Laacher See, for instance, indicate that the magma reservoir has cooled only to about 400°C.



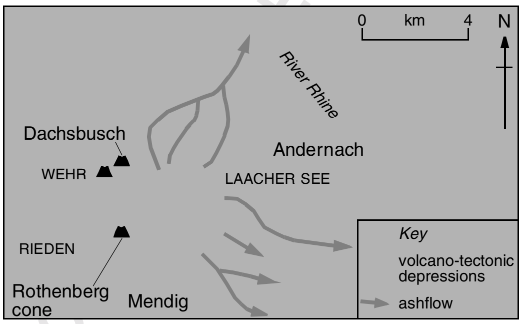
Volcanic zones of the Eifel Massif.

The growth of Rothenberg cone

Rothenberg, which rises on the low ridge separating the Rieden depression from Laacher See is, perhaps, typical of the rather complex evolution of the basanitic–tephritic cinder cones in the East Eifel (Houghton & Schmincke 1986, 1989). It was emitted from six vents aligned on a north-northeast to south-southwest fissure, about 600 m long. The present much-quarried summit of Rothenberg now lies 60 m and originally probably rose about 120 m above its base. The bulk of the volcano is composed of two coalescent cinder cones, although Rothenberg was constructed in six phases of activity. The eruption probably started about 12 000 years ago in an area blanketed by more than 20 m of phonolitic nuée ardente fragments that had exploded from the Rieden depression. These deposits constitute a major water-holding layer and were primarily responsible for the hydrovolcanic explosions from the Rothenberg vents. The first hydrovolcanic eruption formed the small tuff ring, 200 m across, of thin and fine tephritic beds. However, a rapid increase in magma discharge soon excluded any groundwater from the vent and built the first tephritic cinder cone, 65 m high, which eventually buried the tuff ring. Then, when the discharge decreased again, the magma could no longer rise up the main northern vent and could reach the surface only to the south. Here, abundant groundwater was still available in the Rieden layers, and hydrovolcanic explosions immediately generated another set of tuffs. The last two phases occurred when basanitic magma erupted. Activity was only weak on the northern cone, but a new vent formed farther south along the fissure. Hydrovolcanic eruption again began the sequence on the new vent. But once again, as magma discharge increased and eliminated the groundwater, Strombolian eruptions expelled more cinders that formed the southern basanitic cinder cone of Rothenberg, which soon coalesced with its northern predecessor.

EAST EIFEL

The volcanic activity of the East Eifel region was helped by the development of a zone of fault troughs, running west-southwest across the plateau from the River Rhine near Andernach. The eruptions of alkali basalts, tephrites and basanites often formed cinder cones and lava flows, but violent widespread phonolitic explosions of pumice were sometimes followed by volcanotectonic foundering or by extrusions of phonolitic domes. Although hydrovolcanic activity was both powerful and frequent, voluminous lavas were emitted fast enough to prevent the formation of maars here; and the volcanotectonic depressions, such as those at Wehr, Rieden and the Laacher See are at least twice the size of the maars farther west. Two dozen or so basanitic cinder cones predominate in the fault-trough zone east of Laacher See and a similar number of leucitic or leucitic phonolite cones and domes mark the upthrown blocks west of Laacher See (Houghton & Schmincke 1989). Many of the parent vents in both areas are aligned on regional fissures trending from northwest to southeast or northeast to southwest.



Volcanic depressions of the East Eifel massif and the main directions taken by the ashflows emitted from the Laacher See.

The volcanic depressions of Wehr, Rieden and Laacher See seem too large to be maars and too small to be calderas. They are clearly associated with volcanotectonic collapse as well as with violent explosions that often had a distinct hydrovolcanic component. These larger depressions were, perhaps, simply caused by more violent explosions of phonolitic magma in eruptions that reached Plinian proportions.

The Rieden depression is the largest in the East Eifel area and is 2 km broad, stretching 4 km from northwest to southeast. Its edges are sometimes scalloped, which suggests that the depression collapsed intermittently. It contains 15 volcanic vents, which were the likely sources of the thick blanket of pale phonolitic (selbergitic) fragments that filled the depression and radiated more than 5 km from it (Bogaard et al. 1987, Houghton & Schmincke 1989). The fragments were expelled in nuées ardentes, which most probably accompanied the collapse of the Rieden depression, which began 470 000 years ago and climaxed about 410 000 years ago.

A smaller and simpler collapse then occurred at Wehr some 2 km to the northwest. The Wehr depression stretches almost 2 km from northwest to southeast. The phonolitic-trachyte

Laacher See

Situated 40 km south of Bonn, Laacher See is the largest lake and the most famous volcanic formation in the Eifel Massif. It is 2.5 km in diameter and 270 m deep, and lies in the midst of a swarm of tephritic and basanitic cinder cones that rise from a plateau blanketed with thick layers of white pumice (Schmincke & Mertes 1979). Laacher See seems to be a complex ashflow caldera formed by a combination of vigorous explosions and volcano-tectonic foundering. There is no doubt about the explosions. About 11 000 years ago, in the space of perhaps little more than a week, and almost certainly less than a year, Laacher See was the site of a Plinian eruption of over 16 km^3 of fragments and flows of phonolitic ash and pumice that are still over 50 m thick near the vent. The debris covers many adjacent cinder cones and forms a clear indicator bed in deposits far beyond the confines of the region (Bogaard & Schmincke 1984, 1985).

The eruptions were generated by a phonolitic magma in a reservoir situated between 3 km and 6 km below the surface, which had probably evolved from an original basanitic magma that had already erupted the surrounding swarm of cinder cones about 270 000 years ago. The most differentiated, highly alkaline and gas-rich phonolites from the uppermost parts of the reservoir were ejected first, followed by less differentiated crystal-rich phonolites, at temperatures between 800°C and 880°C, as the eruptions concluded. The eruption may have been precipitated a few hours after fresh basanitic magma invaded the reservoir, although it is possible, on the other hand, that the new magma arose only when the old had been ejected from the reservoir (Wörner & Wright 1984).

The eruptions proceeded at a very rapid pace and most of them had marked hydrovolcanic components. The breccias expelled during the initial vent clearing were soon superseded by the Plinian columns of phonolitic fragments. The wind winnowed pumice from the columns and spread it widely, and nuées ardentes surged outwards whenever the columns collapsed (Fisher et al. 1983, Schumacher & Schmincke 1990). The nuées ardentes rushed between the cinder cones and swamped the valleys with as much as 10 m of pumice for up to 3 km around the vent. The finer material spread in a blanket of better-sorted pumice that reached 1 m deep over a wide area of the East Eifel. And the finest materials covered some 700 000 km^2 and reached as far afield as Stockholm, Berlin and Turin (Bogard & Schmincke 1984, 1985). This eruption brought the activity of the East Eifel area to a spectacular, but perhaps temporary, conclusion. However, as new magma apparently invaded the magma reservoir about 11 000 years ago, and fumaroles are still present at Alte Burg, the Laacher See volcano should not be considered extinct.

fragments erupted about 213 000 years ago and, no doubt, mark the initiation of the depression. It has a simple outline and encloses only one vent, although the Dachsbusch cone of alkali basalt also rises on its northern rim. The later eruptions from Wehr covered the Dachsbusch basalts and formed four white layers of phonolitic pumice, dated to 60 000, 52 000, 32 000 and 25 000–12 000 years ago, which were themselves interspersed with basaltic eruptions. The Wehr depression is not entirely extinct, for Welschmiesenmuhle, at its northern end, still manifests fumarole activity.

WEST EIFEL

The volcanic activity of the West Eifel area spread densely over two areas of the plateau centred on Daun, and most of the vents are aligned along en echelon fissures. The basaltic, tephritic and basanitic magmas erupted at intervals that began about 400 000 years ago and ended about 12 000 years ago in the northwest, but lasted only from about 60 000 years until 10 000 years ago in the southeast. The major differences in both these volcanic areas are determined by the presence or absence of groundwater. In the northwestern part of the region, Strombolian eruptions took place along the fissures without water interference and formed tephritic and basanitic cinder cones, such as the Dohm, Hoher List and Radersberg, for instance, and they were often accompanied by small lava flows. Most of these cones have already lost their steepness and sharp outlines after many millennia of weathering.

In the southeast, the eruptions were not only generally more recent, but also were greatly altered by water interference. Although a dozen or so ordinary cinder cones have been formed, the area is dominated by the famous maars (Ollier 1967, Lorenz 1973). These are rounded

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