Introduction

Worlds on Fire takes the reader on a tour of the most spectacular volcanoes in the Solar System. Our odyssey starts logically here on Earth in order to lay the foundations of volcanology. We propose field trips to five of our most representative volcanoes, in order to illustrate the range of eruptive behavior, before turning our sights to other planets.

The structure of the book follows this simple pattern: an introductory text presents the discovery and volcanic "flavor" of each planet (odd-numbered chapters), while a field-trip section describes five landmark volcanoes with proposed itineraries (even-numbered chapters). These hiking sections introduce a fair amount of poetic license, as we follow the footsteps of the *Apollo* astronauts to Hadley Rille, climb the mighty slopes of Olympus Mons on Mars, and drift over the searing landscapes of Venus in a balloon. On Jupiter's fiery moon Io, we cautiously approach erupting jets of sulfur and fountains of ultra-hot lava.

Worlds on Fire is written for the layman, but explores volcanic processes in sufficient detail to serve as a guide book for students of the Earth sciences. The text and illustrations include results from the most recent probes: *Mars Global Surveyor*, *Spirit* and *Opportunity* on Mars, and *Galileo* around Jupiter. The language is kept simple and a glossary at the end of the book defines the more specialized terms sometimes used.

I encourage the reader to start with Chapter 1 to review the basics of volcanism and grasp the concepts that will prove handy in later chapters. It is perhaps the most challenging and dense chapter, so bear with me! But it is also wise to skip sections that appear too detailed or complex; each reader should pick the level of reading that fits him or her best.

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Charles Frankel
Excerpt
More information

The field-trip chapters cover 25 different destinations. One way to enjoy this book is to skip around from volcano to volcano, without necessarily reading the introductory chapters. This reading method provides a condensed and hopefully enjoyable picture of a planet and its volcanic activity.

The knowledge presented in this book has been amassed by scores of planetary scientists. My role consisted in summarizing this body of work for the layman and weaving a story line that assembles so many discoveries and themes into a coherent story. A bibliography is listed at the back of the book. This selection of articles is kept short; it is only a sample of the corpus of research material that is available to interested readers and should serve as gateways to some of the journals that specialize in planetary geology. Likewise, the list of websites is the tip of the iceberg for those who want to surf across the Solar System.

I am indebted to the distinguished reviewers who took the time to read and correct my planetary ramblings and in particular my earlier work, *Volcanoes of the Solar System*, which I use as a starting point for this new book. Therefore, I would like to renew my gratitude to Dr. David Clague, former Scientist-in-charge of the Hawaiian Volcano Observatory; Dr. Harrison Schmitt, lunar module pilot and geologist of *Apollo 17*; Dr. James W. Head III of Brown University; Dr. Sean Solomon of the Carnegie Institution; Drs. Larry Crumpler and Jayne Aubele of New Mexico's Museum of Natural History and Science; Dr. Alfred McEwen of the University of Arizona and Dr. Ronald Greeley of Arizona State University.

I am most indebted to Dr. William Hartmann of the Planetary Science Institute in Tucson for going over the Martian chapters of the present book and checking the most recent data that I discuss, as well as to Rosaly Lopes of the Jet Propulsion Laboratory, who did the same with my chapters on Io and the most recent findings from the *Galileo* probe. They provided me with enlightening suggestions and corrections. The errors and subjective slants that remain are mine only.

Most of the illustrations in this book were graciously provided

by learning and research institutions, and by individual scientists and their publishers. Last, but not least, I would like to thank Pascal Lee of the SETI Institute for suggesting the title of this book: *Worlds on Fire*.

I hope you will sense the passion and dedication that so many people invested in this book. Grab your spacesuit and your helmet and *bon voyage*!

1 Volcanism on Earth

Volcanoes are fascinating. They are aesthetic landscapes as well as a startling reminder of the forces pent up inside the Earth. Erupting fissures and vents spew out molten rock at temperatures topping 1000 °C, and craters belch plumes of ash that can rise high into the stratosphere and radically alter the climate. Volcanism is also the source of mineral ores, the main provider of gases to the atmosphere, and a leading influence in the creation and evolution of life on Earth.

Because of their wide range in chemistry and eruptive behavior, volcanoes come in a variety of shapes and sizes. Elegant cones crowned by summit craters rise along the Pacific rim from Indonesia and Japan to the Aleutian Islands, Cascades, Central America and the Andes. But volcanoes on Earth also include steep domes, giant shields, and fields of small cones that pepper vast areas of the continents and the deep ocean floor. Volcanoes erupt in the open, or below several kilometers of water, or even under ice caps.

Nor are volcanoes restrained to our planet. One of the important discoveries of the space age is the pervasive nature of volcanism throughout the Solar System. Lava fields, shields and domes show up on the Moon, Mars and Venus. Churning lakes of magma and jets of sulfur are active on Io, Jupiter's fiery moon. These new findings have greatly broadened our perspective on volcanism.

Volcanoes serve a purpose. They release the heat pent up inside planets. Volcanoes act as radiators, circulating molten rock, sulfur or hot water through their plumbing systems – a process that carries the calories up to the surface.

WHY IS THE EARTH HOT?

Planets are born hot. The Solar System came into existence through the gravitational collapse of a cloud of gas and dust, four and a half

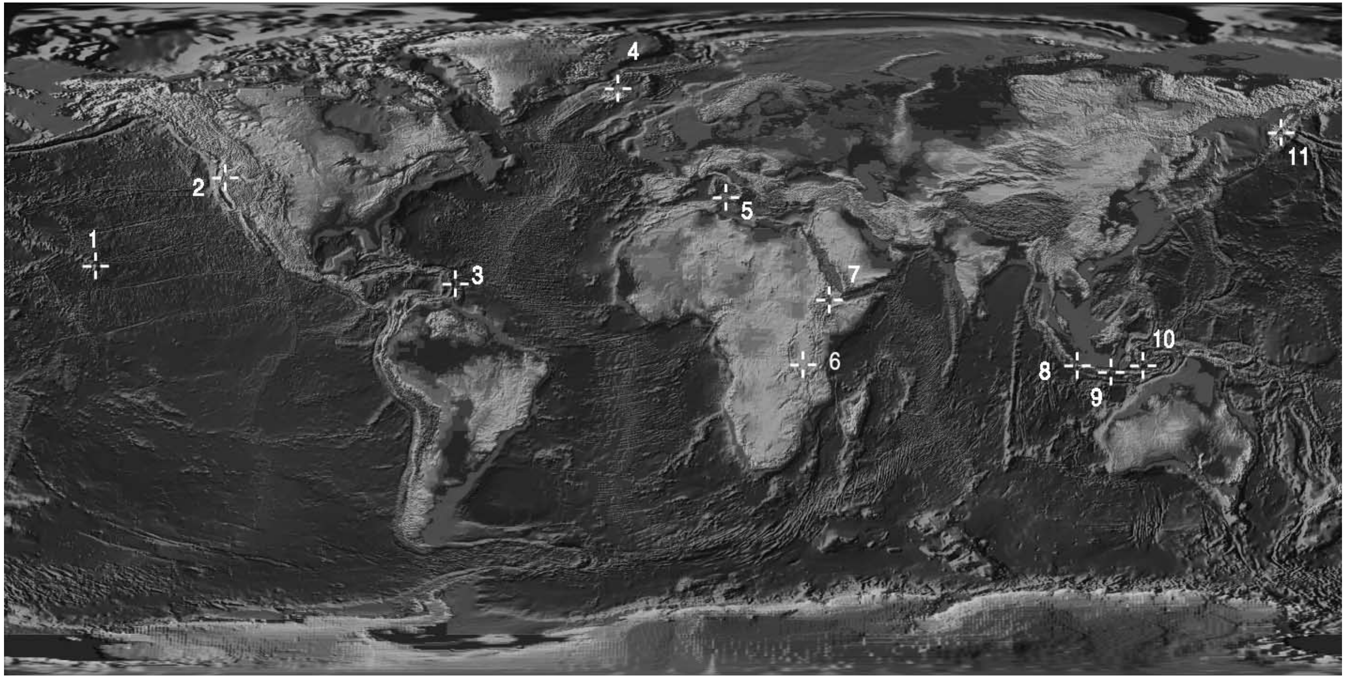

FIGURE 1.1 Topographic map of Earth. Submarine volcanic rifts snake down the Atlantic and the East Pacific. Volcanic island arcs (subduction zones) are prominent in the West Pacific. The major volcanoes discussed or illustrated in the text are indicated by numbers. (1) Kilauea; (2) Mount Saint Helens; (3) Mount Pelée; (4) Krafla; (5) Etna; (6) Ol Doinyo Lengai; (7) Erta Ale; (8) Krakatao; (9) Merapi; (10) Tambora; (11) Kamchatka volcanoes. Credit: JPL-Caltech, U. S. Geological Survey.

billion years ago. The heart of the collapsing system became the Sun. Around the new-born star, the leftover matter collected into swirling lanes of debris – nuggets of rock and ice that slammed into each other to ultimately form the planets. This *accretion* phase was highly energetic, each new impact bringing a blast of heat to the growing planet. Most of this heat was radiated back into space, but a substantial amount remained trapped in the growing body, as layer upon layer of hot debris piled up at the surface. Through this process a planet like the Earth might well have reached a temperature in excess of 2000 K (around 2000 °C) as it reached its adult size in a few tens of millions of years. Its outer layers were probably entirely molten by the heat in a glowing "magma ocean" hundreds of kilometers deep. One giant impact in particular – that of another burgeoning planet – blasted the Earth early in its history and injected a bonus of energy into its deepest layers. As we shall see in Chapter 4, material that was flung into space by this giant collision rapidly coalesced in Earth orbit to form the Moon.

FIGURE 1.2 Mount Etna (Sicily), photographed by astronauts aboard the International Space Station. Volcanoes evacuate the heat pent up inside planets. Credit: NASA/JSC.

Planetary accretion is the most spectacular process that heated up the Earth. But simultaneously, a second heating process provided its share of calories – an inner form of gravitational energy. Because the Earth was partially molten, different elements like iron and lead, sodium and potassium, behaved according to their density and buoyancy, some rising to the surface while others sank towards the center. Any sinking body releases energy as it drops from a high level to a lower level within a gravitational field, and the sinking of dense elements like iron and lead released considerable amounts of heat as they trickled towards the center. This should have raised the planet's temperature by an additional 1000 K or so, above the 2000 K already reached by the accretion process. Besides these "outer and inner forms" of gravitational energy, there was a third source of planetary heat: radioactive decay. Elements like uranium are unstable and break up over time into lighter atoms, releasing energy in the process. This nuclear form of heating was particularly efficient in the early days of the Earth, when radioactive atoms were plentiful and decayed readily, such as the highly unstable aluminum-26 that expended half of its stock (known as the element's *half-life*) in the first few million years of Earth history.

Other elements tick away at a slower rate, like potassium-40. Its numbers are cut in half in about 1.3 billion years, so that only 10% of this radioactive "fuel" is still left inside the Earth today. With half-lives of 4.5 and 12 billion years, uranium-238 and thorium-232 have expended only one half and less than one quarter of their stock respectively, so that they still play a major role in the heating of the planet. In fact, 80% of the heat reaching the Earth's surface today is due to radioactive decay and 20% to the accretion of the planet and the sinking of the core, slowly distilled over the aeons.

CORE, MANTLE AND CRUST

Because the minerals that make up the Earth are remarkable insulators – we use rock wool to insulate our homes – internal heat travels very slowly to the Earth's surface. This heat stacks up because of the

Distribution of volcanoes on Earth

There are approximately 1500 volcanoes on Earth that have erupted since the dawn of civilization, 10000 years ago [see the Global Volcanism Network of the Smithsonian Institute]. Of these, 550 volcanoes erupted at least once over the past 2000 years.

Today, an average of 20 volcanoes are erupting around the globe at any one time (above sea level), including 17 that have been doing so semi-permanently over the past 20 years. This select list includes Etna and Stromboli in Sicily, Arenal in Costa Rica, Sakura-Jima in Japan, Semeru in Indonesia, Erta Ale in Ethiopia, Erebus in Antarctica, Kilauea in Hawaii. The list of "old faithfuls" is topped by "surprise" eruptions from other volcanoes (3 or 4 occurrences across the globe at any one time). Over a one-year interval, 60 different volcanoes erupt.

The numbers of volcanoes on Earth grows especially large when one considers the small cones and domes that make up "volcanic fields." A few hundreds of meters tall and several hundred meters in diameter, they are clustered in groups of several hundreds (for example, the Springerville volcano complex, Arizona: 409 vents). There are tens of thousands of these "midgets." On the ocean floor, they are especially abundant in the central rift valley of the mid-ocean ridges, where they stretch out in long chains. Their numbers reach in the millions.

The magnitude of eruptions is inversely proportional to their frequency. Small events are the most frequent. Several eruptions per year emit 0.01 km^3 of lava or ash, but only one in a decade reaches 1 km^3 (such as Mount Saint Helens in 1981). An eruption of 10 km^3 occurs on the average once a century (Krakatao in 1883, Katmai in 1912) and one of 100 km^3 once in a millenium (Tambora in 1815). Great ignimbrite eruptions on the scale of 1000 km^3 are expected only once every 100000 years (the last one created the Toba caldera, Indonesia, 64000 years ago).

Two volcanoes in the East African Rift. Credit: NASA/JPL/NiMA.

imbalance between heat production inside a planet and heat release at the surface. Heat production is proportional to the quantity of radioactive matter locked up inside a planet and thus to its volume. On the other hand, the escape of heat at the surface is proportional to the planet's area. For a planet with a large radius, like the Earth, the discrepancy between its volume and its area is large, and the cooling cannot keep pace with the heating. The temperature rises. Ultimately, it can reach the planet's melting point.

One would expect the deepest layers of the Earth to be the hottest, and indeed they are. But they are not necessarily molten. This is because temperature is not the only factor involved; pressure also comes into play, as does the composition of the heated material.

The balance of factors is complex and leads to a stratified

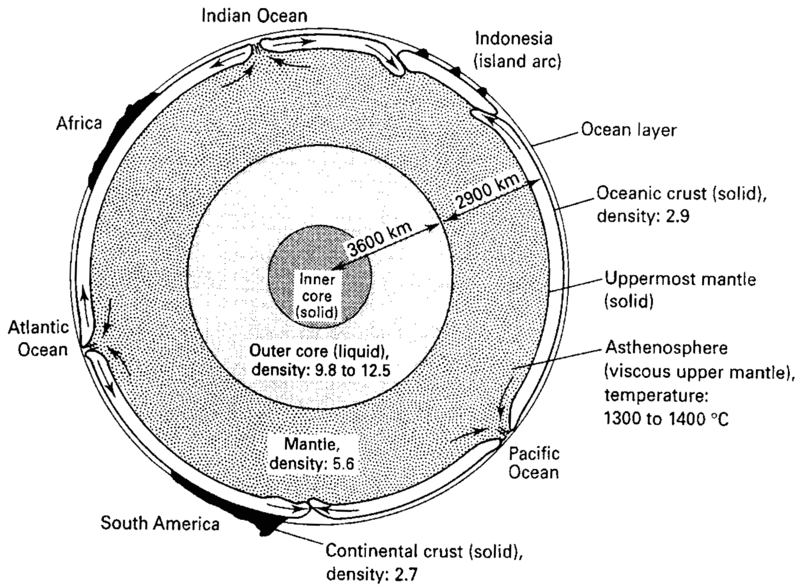

FIGURE 1.3 Internal structure of the Earth. Soon after its accretion, the planet segregated into layers of contrasting compositions and densities: heavy iron sank to form the core, while silicates ended up in the mantle, capped by a thin crust. Credit: adapted from La Documentation Française, Documentation photographique 6107, Les Volcans, 1990.

planet, divided from bottom to top into a core, mantle and crust. Although we do not have access directly to the lower layers – our deepest mines reach only 3 km below the surface and our deepest drill holes a mere 12 km – an indirect assessment can be made through earthquakes. Seismic waves that travel through the planet experience variations in amplitude, speed and direction as they cross through layers of different composition and physical state. These numbers, compiled with other clues, allow us to sketch out a cross-section of the Earth.

At the center of the planet, seismic data reveal a solid *inner core* of iron, perhaps mixed with some nickel or sulfur. The temperature reaches 6000 K (about 6000 °C), but the pressure is so great that melting cannot take place. This inner core extends from the center of the Earth (6378 km) to a specific level, 5150 km from the surface, where the pressure has fallen off faster than temperature and allows melting to occur. Here begins an *outer core* of liquid iron – the only truly liquid layer inside the Earth. Electrical currents flow through this shell of liquid iron and generate the powerful magnetic field that we experience at the surface. This liquid iron shell terminates abruptly 2890 km from the surface, where it is overlaid by a layer richer in silicon, magnesium and aluminum: a *mantle* of interlocked minerals. There is a significant drop in temperature across the boundary – unpoetically labeled the *D-prime* zone – so that the lower mantle is solid. The temperature at the base of the mantle is 2500 K (2200 °C).

Up to the surface, the subtle interplay of pressure and temperature keeps the mantle solid, except in a zone approximately 200 to 100 km below the surface, where the fast-declining pressure lets the mantle adopt a mushy state, with drops of melt collecting along mineral boundaries. This zone is named the *asthenosphere* ("weak sphere" in Greek). It is the prime region where rock melt is generated, which is called *magma*.

Over the aeons, a large amount of magma has risen to the surface, erupted, and cooled to form a solid outer shell, a few tens of kilometers thick. This is the Earth's *crust* on which we live.