Chapter 2
Soils Born of Fire

Erupting volcanoes create new land surfaces on which new soils develop, Kiluaea, Hawaii

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Introduction

> "Nature is often hidden, sometimes overcome, seldom extinguished"
>
> Francis Bacon, 1625

Volcanoes are one of Earth's most fearsome exhibitions of power. Erupted lavas and tephra (volcanic ash) are a source of materials that weather to form new, and often exceptionally productive, soils.

Volcanoes create and shape landscapes. Whether building huge shield volcanoes, such as the Hawaiian Islands, or coating landscapes with far-flung pumice or tephra from explosive eruptions, such as Crater Lake in Oregon, USA, the effects, and products, of volcanic eruptions are a source of fascination.

People who live in the paths of volcanic eruptions understand the terror of blasts of hot fiery materials or mudflows that extend far beyond the confines of the volcano itself. Mud falling on homes and fields, the inconvenience of airplane flights canceled, and the surreal beauty of bright red sunsets all occur due to volcanic ash, aerosols, and gases, impacting audiences at ever greater distances from the source.

Soils in regions impacted by fallout from volcanic activity contain a memory of the eruptions that have occurred (Fig. 2.1). Burial by volcanic deposits may capture moments in time that are a record of life's tragedy, for instance, the chilling images of people in Pompey, Italy, buried by the eruption from Vesuvius in 79 AD.

Fig. 2.1 This soil, formed in volcanic deposits in the Gunma prefecture of Japan, contains the memory of a long history of volcanic activity. The topsoil includes scoria from the 1783 eruption of Mt. Asama, some 80 km away. The white pumice was erupted from Mt. Haruna about 1400 years ago. The dark-colored buried topsoil contains evidence of cultivation having occurred at this site about 1500 years ago prior to the pumice eruption. The bright brown gravelly layer toward the base of the profile was erupted from Mt. Asama about 15,000 years ago. Below the bottom of this picture is a distinctive tephra erupted from the Aira caldera, about 1000 km away, about 30,000 years ago

Volcanic Landscapes

In order to understand the soils formed from volcanic materials, we need to know something of the volcanic landscapes in which they occur. There are three main kinds of volcano: basaltic, andesitic, and rhyolitic. Each has a distinctive mineral composition and eruption style and each forms a different array of landscapes and soils. Volcanoes are generally associated with tectonic plate boundaries (Fig. 2.2). However, there are also volcanoes, such as the Hawaiian Islands, that are on "hot spots," within tectonic plates, where molten rock from the mantle flows up to the earth's surface.

Basalt volcanoes erupt a dark-colored magma that is rich in iron and magnesium with less than 50% silica. Basaltic magma rises rapidly to the surface from the Earth's mantle. Basalts are the hottest magmas and generally erupt as very fluid lavas or as fire-fountain eruptions that fling magma into the air, where it cools, solidifies, and lands as basaltic scoria. Basalt is erupted at spreading tectonic plate margins, most of which are beneath the sea and at intraplate hot spots. The very hot, fluid, basaltic lava may flow out over long distances to form huge, low-sloping "shield"-shaped volcanoes (Fig. 2.3). Where scoria is erupted in "fire fountains," it forms small cones, often on top of a larger shield volcano.

Andesite volcanoes form on tectonic plate boundaries where one plate is being subducted beneath another. As the subducted plate dips deep into the Earth's crust, it gets hot and some of the material melts and returns to the surface erupting as andesite. Andesite volcanoes have an "intermediate" composition (with 50–70% silica) being a combination of material from the Earth's silica-rich surface crust and the iron-rich mantle. Andesite volcanoes tend to alternate between explosive eruptions that blast tephra into the air, and lava flows of viscous magma that do not spread very far. Thus andesite

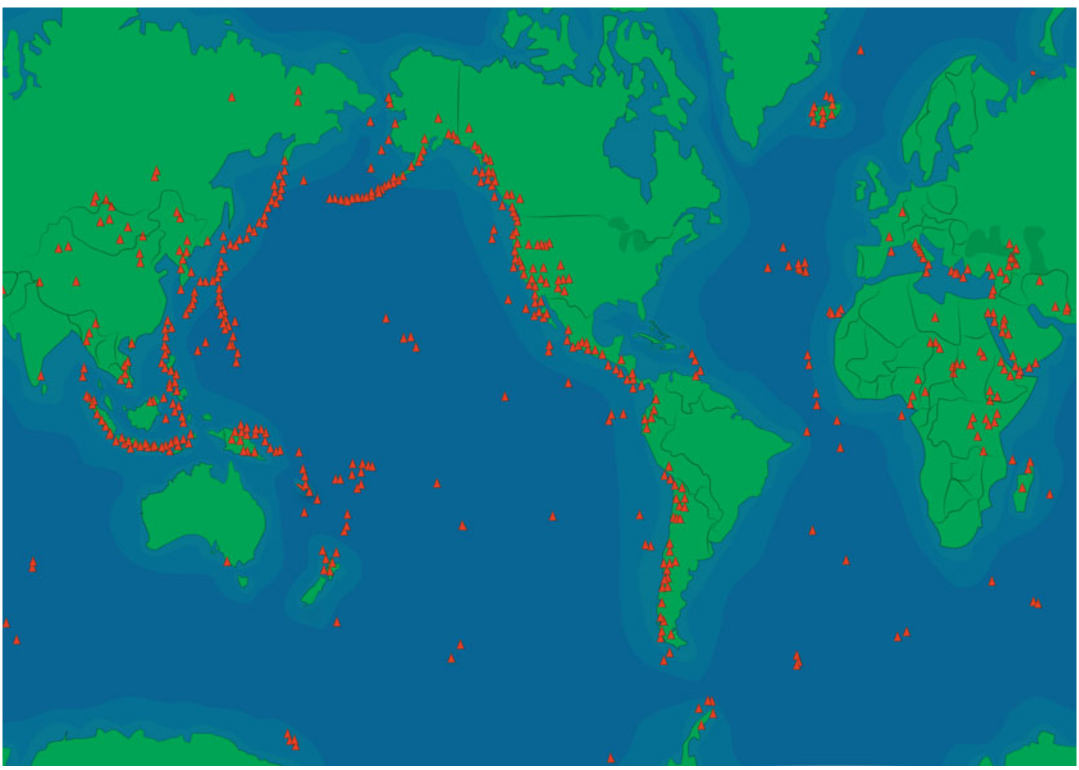

Fig. 2.2 Global distribution of volcanic activity

Fig. 2.3 The low-sloping profile of a basalt shield volcano, Mauna Loa, Hawaii

Fig. 2.4 Mt. Fuji in Japan has the characteristic cone shape that we associate with andesite volcanoes. Fuji has erupted both basaltic and andesitic materials (Photo: David Lowe)

volcanoes build up layers of magma and volcanic ash to create beautiful cones such as Mt. Fuji in Japan (Fig. 2.4).

Many of the steep-sided andesite volcanoes have a large surrounding "ring plain," such as the one around Mt. Taranaki in New Zealand (Fig. 2.5). The ring plain is built up from the layers of tephra that fall from the air and also from rapidly moving, water-saturated mudflows (called lahars) that periodically flow down from the upper slopes of the volcano. As the slope flattens, near the base of the volcano, the lahar flows lose momentum and the material comes to a halt. A hummocky landscape forms which, over time, is colonized and stabilized by vegetation.

Rhyolite volcanoes erupt magmas that are formed from melting of silicic crustal material on subducting tectonic plate margins. Rhyolite magma is high in silica (>70 %) and extremely viscous. Huge pressures build up which, when finally released, result in the largest, most explosive eruptions on Earth.

When rhyolite volcanoes erupt, they eject vast volumes of material high into the atmosphere in a huge eruption column. In some cases the column collapses and hot pumice-rich, gas-laden material is blasted across the landscape, as a fast-moving, ground-hugging, pyroclastic flow that buries or

Fig. 2.5 The ring plain of Mt. Taranaki in New Zealand. The circular change in color around the mountain is the boundary of the Egmont National Park where native forest gives way to dairy pastures. A radial drainage pattern is evident as rivers all flow outward from the top of the mountain, across the ring plain

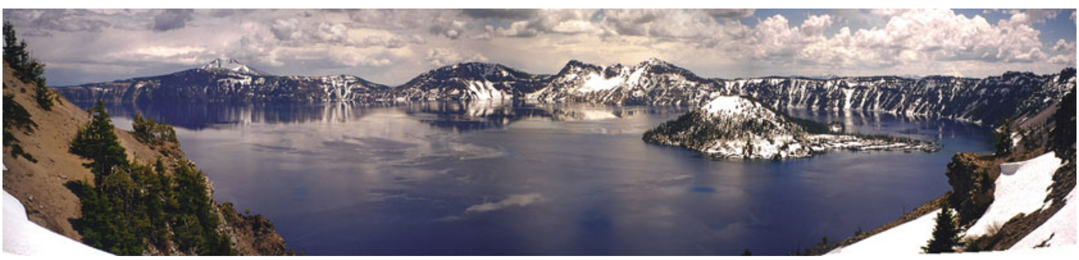

Fig. 2.6 Crater Lake in Oregon is a caldera formed by collapse of the land following a rhyolitic eruption of about 50 km^3 of material about 7700 years ago

removes everything in its path. Extensive pumice deposits are emplaced, and where the material is hot enough, it fuses together to form a rock called welded ignimbrite. The finer tephra material can be carried thousands of kilometers before settling to the Earth's surface.

Krakatoa, an Indonesian island that erupted in 1883, generated one of the largest historically recorded rhyolite explosions. The blast was heard over 4000 km away and tephra, aerosols, and volcanic gases reached up to the stratosphere, causing global climate cooling which lasted about 5 years.

Once a rhyolite eruption ceases, the ground from which the material was erupted collapses, leaving a huge hole, called a caldera. Often the resulting caldera fills with water to create a lake, for example, Crater Lake in Oregon (Fig. 2.6).

Hawaii: Steam Heat and New Rock

Nowhere else on earth, except perhaps Iceland, is the fiery birth of volcanic soils more evident than in the Hawaiian Islands. People travel from all over the world to see lava flowing from the erupting craters of Kilauea (Fig. 2.7). The Hawaiian Islands sit over a hot spot. Over time the ocean floor has gradually moved across the hot spot giving rise to a series of volcanoes of increasing age with increasing distance from the present-day activity (Fig. 2.8). Thus the oldest eruptive materials (erupted about five million years ago) are found in Kauai, with the youngest material, likely to be erupting as you read this, on the Island of Hawaii.

In the warm, wet climate on the east side of Hawaii (the “Big Island”), it is not long before the newly erupted rock material begins to weather, plants gain a toehold, and soil development gets underway. In the drier western regions, and in the colder high-altitude zones, soil development is slower. The large range in the age of the rocks, the climate, and the vegetation in the Hawaiian Islands leads to a wide variety in the soils that form.

Thus the Hawaiian Islands contain not only a record of the formation of new rock material but also a sequence of soils, ranging from the first steps toward soil formation in the newly erupted material to soils that have developed over millions of years. The new lava flows cool to form hard rock, and their dark color means they heat up in the sun, making the rock surface particularly inhospitable. Where the lava flows have cut through preexisting forests, there is a ready source of nearby seeds and so the plants gradually colonize the new lava (Fig. 2.9).

At first just a few pioneer plants become established, but gradually vegetation gains a hold, the rocks start to weather and more plants are able to survive. After a few thousand years, where the climate is warm and wet, rocks weather, clays are formed, and tropical forest becomes established (Fig. 2.10). Where the climate is dry, weathering is slower. Salts accumulate in the soils and the vegetation is prone to fire damage ensuring survival of only the toughest plants (Fig. 2.11).

Fig. 2.7 New lava flowing from an eruption vent on Kilauea volcano in Hawaii (Photo: Annette Rodgers)

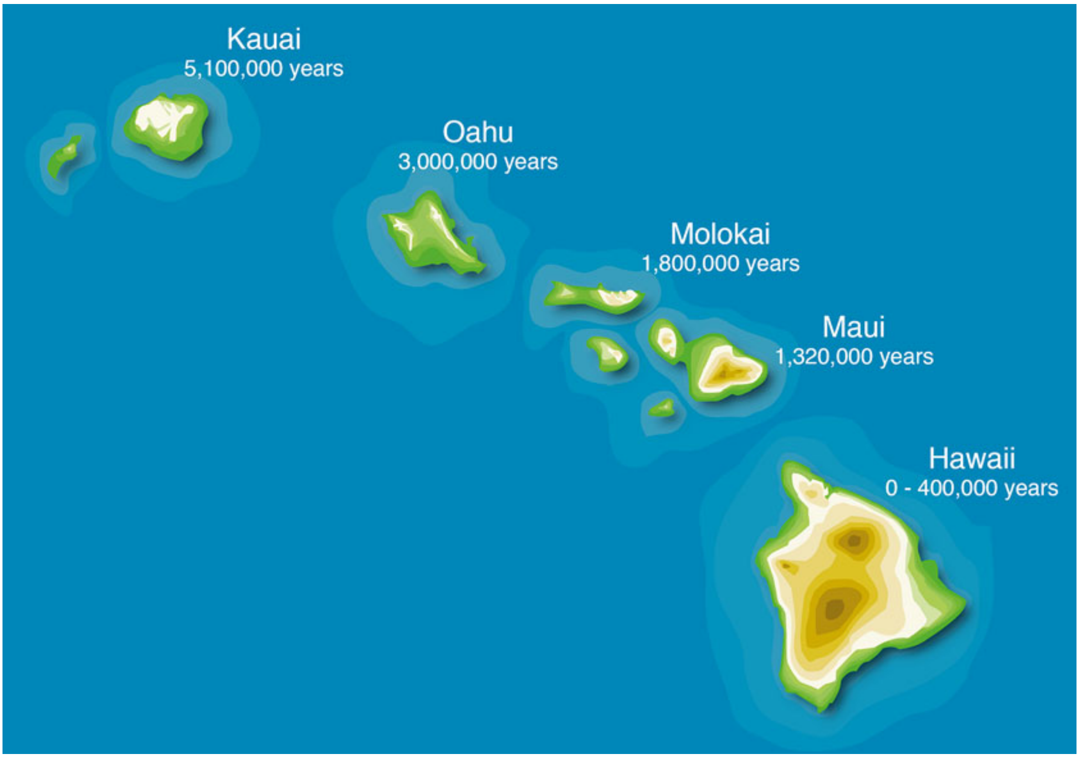

Fig. 2.8 Map of Hawaiian Islands showing ages of volcanic activity

Fig. 2.9 Basalt formed from lava that was erupted from Kilauea in 1973. In these photos taken 40 years after the eruption, the very start of soil development and plant establishment is occurring. The larger, distant trees that survived the eruption provide a source of seed and organic matter to help start new soil formation

Fig. 2.10 Tropical rain forest and the related clay-rich soil formed on ancient lava deposits in the high rainfall on the east side of Hawaii (the “Big Island”)

Fig. 2.11 The dry, fire-prone environment and relatively weakly weathered, salt-rich, rocky soil on lava on the west side of the Island of Hawaii

Mount Saint Helens

The Cascade Mountains, in the northwestern USA, are part of the "Ring of Fire" that surrounds the Pacific Ocean. The Cascades have numerous volcanoes, and Mt. St. Helens was one of the most scenic and symmetrical volcanoes with its lower slopes blanketed with forests (Fig. 2.12). Tribal legends called the mountain "Loo-Wit" who was a young and beautiful maiden fought over by two young chiefs (two nearby volcanoes: Mt. Hood and Mt. Adams).

The volcanoes of the Cascade Mountains produce mostly volcanic ash (tephra) and pumice, rather than lava. Tephra buries older soils when it is deposited on a landscape. Many ash eruptions have occurred over thousands of years, and old soils have been buried by new layers of tephra here (Fig. 2.13) just as they have in Japan (Fig. 2.1).

When Mt. St. Helens erupted, in 1980, the top and much of the north side of the mountain were blown to pieces (Fig. 2.14). A very destructive process! Volcanic ash and rock fragments were spread for hundreds of kilometers, and all of the forests on the north and northeast side of Mt. St. Helens were killed and any preexisting soil was buried or destroyed (Fig. 2.15).

In the years since the 1980 eruption, and the destruction of the forests to the north, life has reentered the landscape and a new ecosystem has begun to develop (Fig. 2.16). The process of soil formation had to start over again in many areas after the 1980 eruption (Fig. 2.17). Young soils often contain very little nitrogen, a nutrient essential for plants. Thus many of the first plants to colonize the ash and pumice after the eruption were nitrogen-fixing plants, which means they have symbiotic bacteria in their roots that gather nitrogen from the atmosphere and share it with the plant. Even in areas where there are remnants of the old soils, numerous nitrogen-fixing plants will enter. As time passes, nitrogen accumulates in the soil along with organic matter and other nutrients. This allows other vegetation to grow that cannot fix nitrogen. As more vegetation grows, the rate of soil formation will also increase. Eventually, forests will return.

Fig. 2.12 Mt. St. Helens and surrounding forest prior to the 1980 eruption (Photo: United States Geological Service)

Fig. 2.13 Soil profile photographed in the 1970s shows an A horizon over B and C horizons that are mostly small pieces of pumice mixed with finer material. At the bottom is an A horizon formed in a soil that was buried under later eruptions

Fig. 2.14 The expanding "mushroom cloud" from an eruption of Mt. St. Helens in 1980 was visible 150 km away in Seattle

Fig. 2.15 The powerful blast from the 1980 eruption flattened the forest on the north side of the volcano. Trees lay on the ground pointing directly away from the center of the eruption (the crater of Mt. St. Helens is in the distance). It took tremendous force to flatten this forest which is several kilometers from the volcano

Fig. 2.16 Many nitrogen-fixing lupines now grow around Mt. St. Helens. Part of the crater is in the background

Fig. 2.17 Two soils near Mt. St. Helens after the 1980 eruption. *Left*: soil formed in about 30 cm of 1980 ash with an older buried soil still evident beneath. *Right*: soil formed in newly deposited pumice with little soil development. Over time an A horizon and the rich brown color evident in the soil of Fig. 2.13 will develop

Raining Mud: The 1886 Eruption of Mt. Tarawera in New Zealand

Mount Tarawera, a volcanic dome complex near Rotorua, in New Zealand, came to life on June 10th 1886 (Fig. 2.18). A rift opened along the summit of the volcano and a fire-fountain eruption of basaltic scoria commenced. The rising magma intercepted two adjacent lakes, causing an explosive steam-based eruption.

The preexisting landscape, including a famous tourist attraction, the pink and white silica terraces (Fig. 2.19), was destroyed. A gray mud rained down over the region much to the amazement (and in some cases terror) of the more distant residents who, in the days before radio, had no idea what the material was or where it had come from. Ash clouds were observed on ships up to 1000 km north of New Zealand.

Explosions from the eruption were heard hundreds of kilometers away in Auckland and Wellington, causing some people to think a war must have broken out. Several villages within about

Fig. 2.18 Painting of the Tarawera eruption by Ronald Cometti in 1986 based on historical accounts (Reproduced with permission of the copyright holder: R.J. Kearn. www.tarawera.com)

6 km of the mountain were buried, and about 120 people were killed as a result of the eruption. Altogether about 2 km^3 of material was erupted from the mountain leaving a rift across the mountaintop (Fig. 2.20).

In some places the mud deposited during the Tarawera eruption was eroded into a large-scale hummocky rill pattern, possibly by water-rich outfall from the eruption or by rainfall immediately after the eruption. The surface then stabilized and became revegetated; however the hummocky erosion pattern is still visible in many areas over 100 years after the event (Fig. 2.21).

Vegetation became established and a new topsoil is forming (Fig. 2.22). Farmers added fertilizer and grass seed to hasten recovery of the productive potential of the land. Further from the source of the eruption, where only a few millimeters of tephra was deposited, it became mixed into the existing soil.

Fig. 2.19 The "white terraces" painted prior to the 1886 eruption when the terraces were destroyed, buried, or lost. Painted by Carl Kahler (Photographed with permission of Chateau Tongariro)

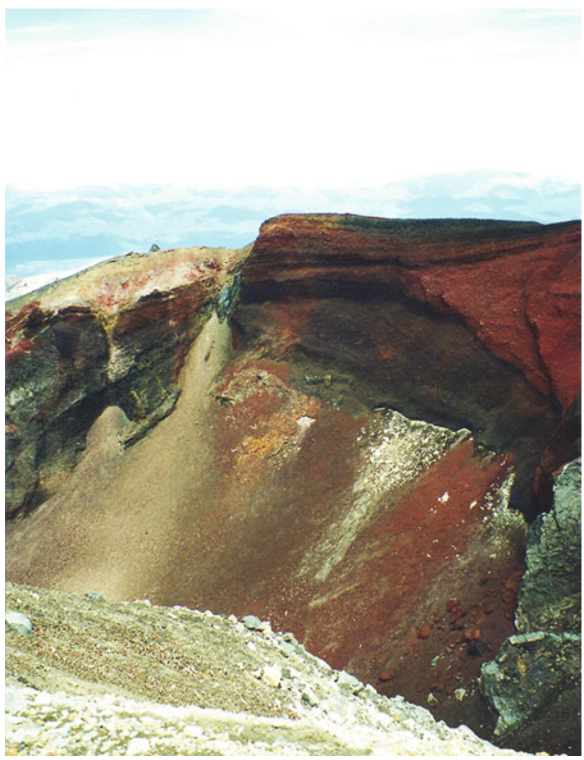

Fig. 2.20 The rift that formed across the top of Mt. Tarawera in the 1886 eruption. The dark reddish and black deposits are from the 1886 basaltic eruption

Fig. 2.21 The rill-eroded hummocky landscape formed in material deposited during the 1886 Tarawera eruption

Fig. 2.22 A thin new topsoil has formed in the gray tephra deposit in the century since the eruption. The buried soil that formed the ground surface prior to the 1886 eruption is evident beneath the gray tephra layer

The Taupo Pumice Eruption

Lake Taupo forms the heart of the North Island of New Zealand (Fig. 2.23). The serene, clear water lake was born of some of the largest volcanic eruptions known. The lake (Fig. 2.24) fills the gigantic collapse feature (caldera) formed after a series of eruptions. Huge volumes (>500 km^3) of material have been blasted into the atmosphere and spread across the surrounding landscape with at least 28 recognized eruptions in the last 26,000 years.

The most recent major eruption from Taupo occurred about 1800 years ago (232 AD ± 10 years), which was before humans reached New Zealand. Tephra was blasted about 50 km up into the atmosphere. When the eruptive column collapsed, hot ground-hugging (pyroclastic) debris flows raced across the landscape for up to 80 km from the source leaving deposits over 100 m deep near the present-day lake. Some of the finer material would undoubtedly have stayed in the atmosphere for some months and circled the Southern Hemisphere.

The resulting Taupo pumice deposit (Fig. 2.25) mantles the entire landscape around Lake Taupo with thicker deposits ponded in valleys and thinner coatings on ridges. The pristine forest was knocked over in the blast, incinerated, and buried. Within the pumice the charcoal remains of the burnt forest are easily seen. Scientists have mapped out the angle of the fallen forest trees, and like a set of compass needles, they all point back to the source of the blast near the northeastern edge of Lake Taupo. The charcoal has been carbon-dated to help determine the date of the eruption.

For some time after the Taupo pumice eruption, the central North Island landscape would have resembled a moonscape with frequent dust and sandstorms as the winds picked up and moved material around. All the rivers and streams were choked with pumice for many years as each successive rainstorm eroded more unconsolidated material into the overloaded waterways. Even today, if you visit beaches in the North Island of New Zealand you can find Taupo pumice washed up with the tide as the pumice material is still being gradually redistributed, via the rivers, through the landscape.

Vegetation became reestablished, until covering the surface and stabilizing the new landscape. Over time organic matter built up to create a thin topsoil (Fig. 2.26). Where the pumice layer was not so thick, the plants gradually got their roots into underlying buried soils, and thus could thrive, in turn contributing organic matter to help build the new topsoil.

Fig. 2.23 Location of Lake Taupo, the source of the Taupo pumice eruption, in the North Island of New Zealand

Fig. 2.24 Lake Taupo fills the main caldera (or collapse feature) that formed following a huge rhyolite eruption 25,400 years ago that deposited tephra as far away as the Chatham Islands 870 km from New Zealand. Pumice from the most recent (232 AD) eruption is evident, washed up on the lakeshore in the foreground

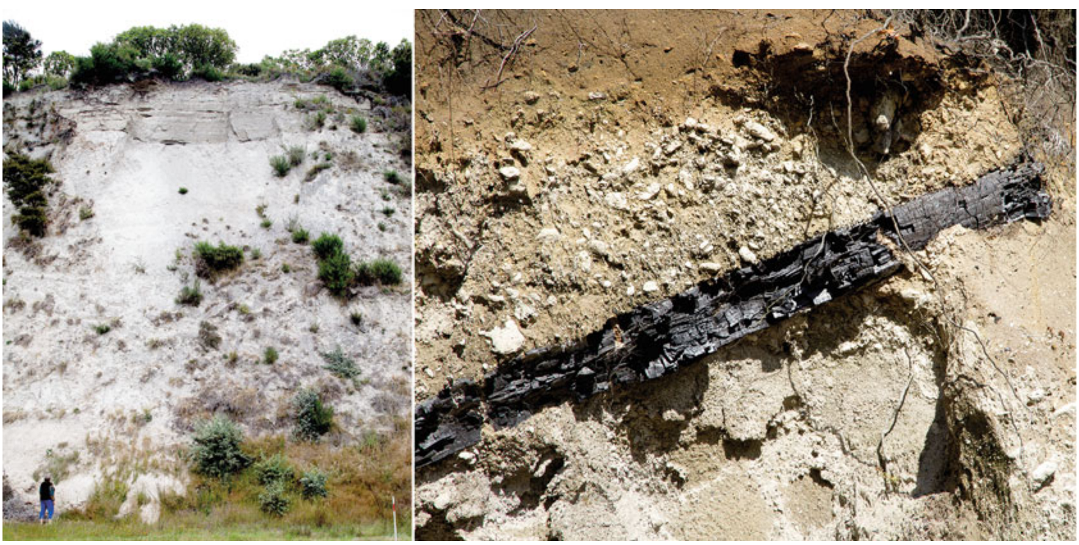

Fig. 2.25 Taupo pumice exposed in a cliff. *Left*: near the eruption source, the pumice can be over 100 m deep. *Right*: carbonized logs within the Taupo pumice, 60 km from the eruption source, were forest trees that were knocked over by the explosion and mark the direction of the blast. Here the white pumice is overlain by younger, brown-colored tephras from more recent andesite eruptions from neighboring volcanoes

Fig. 2.26 Taupo pumice soil has a topsoil developed over weakly weathered pumice. The thickness of the pumice generally decreases with increasing distance from the eruption source (Photo: Glen Trewick)

Jeju, Korea: A Land of Wind and Stones

Situated at the southern end of the Korean Peninsula, Jeju is an island formed from basalt volcanoes, some of which last erupted less than 10,000 years ago. The people of Jeju describe their island as the land of wind and stones. Much of the erupted material that formed the island is highly porous scoria, as evidenced by layers of rubbly eruptive deposits and the Dolharubang ("stone grandfather" statues carved from basalt scoria) that watch over the lands (Fig. 2.27).

The resulting soils (Fig. 2.28) are stony and highly porous, such that traditional rice growing is not possible as water will not pond on the soil surface. However, the soils have been cultivated for over 1000 years to produce vegetables and citrus fruit. The stones that are a great nuisance for cultivation have, over the centuries, been collected up and formed into low walls, known as Batdam (Fig. 2.29). There are over 22,000 km of Batdam on Jeju Island. The Batdam are referred to as the "20 000 km black dragon" as they resemble a long black dragon winding through the landscape.

The Batdam are valued as an iconic feature of the Jeju landscape and an important part of the agricultural heritage of the island. Batdam perform a number of useful functions, marking field and crop boundaries (Fig. 2.30). Jeju Island is prone to strong winds as well as heavy seasonal rainfall. The Batdam provide a windbreak and prevent surface water from flowing over long distances, thus providing an important mechanism for preventing soil erosion. The windbreaks also help protect crops from wind damage. The Batdam provide fences to prevent the horses, a legacy of the Mongol arrival about 1700 years ago, and other wandering animals from damaging cultivated fields and orchards.

Fig. 2.27 The soil parent materials of Jeju Island have been erupted from predominantly basalt volcanoes. *Left*: a coastal outcrop in which the products from many eruptions are evident. *Right*: one of Jeju's many Dolharubang (stone grandfathers) carved from local basaltic scoria

Fig. 2.28 A stony soil typical of those on Jeju Island formed in the basaltic volcanic deposits

Fig. 2.29 Batdam (stone walls built from basaltic scoria boulders removed from adjacent soils) winding through the landscape of Jeju

Fig. 2.30 Cultivated fields in Jeju, Korea, surrounded by Batdam (stone walls) constructed from scoriaceous boulders gathered from the fields

Celebrating the Productivity of Volcanic Soils

When new volcanic material accumulates in thick deposits, it buries the landscape and destroys the preexisting soil and vegetation, so the process of soil formation starts again from scratch. Weathering processes begin and gradually nutrients are released, clays start to form, plants become established, and organic matter starts to accumulate, and thus a new soil develops. Basalt and andesite lava flows and tephra deposits weather to productive, nutrient-rich soils that support a wide range of crops (Fig. 2.31). In warm wet climates, weathering processes act strongly, so soils on older lava flows eventually become highly weathered to infertile clays and oxides with the nutrients leached out. Where unconsolidated tephra deposits occur, soil forms more quickly than it will on solid rock.

Where andesitic volcanic ash falls, the fine tephra allows plants to establish within a few months of the eruption and soils form relatively quickly. Andesitic tephra is relatively nutrient rich and forms soils with excellent physical properties. Where soils have been built up from many thin layers of tephra, the preexisting soil is not destroyed, and with each new eruption, material is added to form soils with excellent properties for supporting plant growth (Fig. 2.32).

Soils formed from andesitic and rhyolitic tephras often weather to form a clay mineral called allophane. Allophane makes a soil soft and friable with a low density so plant roots can easily extend deep into the soil to extract the generous amounts of water stored there. Thus plants can survive extended dry periods more readily in allophanic soils than in many other soils.

The friability of soils formed on andesitic tephra means they are easily worked to create great seedbeds and so are excellent for growing vegetables including root crops such as carrots and potatoes (Fig. 2.33). The main drawback is that allophane has tremendous capacity to hold onto phosphorus stopping plants from accessing it. Thus to maximize crop growth, it is best to add smaller amounts of phosphate fertilizer more frequently on allophane-rich soils so that the plants have a chance to absorb the fertilizer before it all becomes bound by the soil.

Fig. 2.31 Volcanic soils on basalt support a wide range of crops. *Left*: pineapples growing on an old soil formed from basalt in Puerto Rico need fertilizers to be productive. *Right*: citrus fruit growing in soils formed from basalt in Jeju, Korea

Fig. 2.32 Soil formed from andesitic volcanic ash. The thick, dark topsoil is the result of a high organic matter content due to the great soil conditions for plant growth. The soil is friable, so it is easy for plant roots to penetrate deep into the soil

Fig. 2.33 Productive soils formed on andesitic and basaltic tephras in Japan are friable and easily plowed to form excellent seedbeds. *Left*: planting out vegetable seedlings. *Center*: onion crops thrive. *Right*: extensive cabbage plantings on higher altitude soils formed on tephra

Soils formed on pumice and ash materials erupted from rhyolite volcanoes are often extremely low in nutrients as rhyolite is very high in silica with low quantities of other essential elements such as potassium or magnesium. Where the pumice layers are thick, it is often difficult for plants to establish. Thin pumice layers may allow plant roots to access underlying buried soils and thus grow well once established.

When people first attempted to undertake pastoral farming on the pumice soils in the central North Island of New Zealand, the sheep and cattle became ill and died from a deficiency disease that became known as "bush sickness." Pine trees were found to grow well as their roots penetrate deeply, going through the pumice to the underlying buried soils, and they did not suffer nutrient deficiency problems. Thus large areas of New Zealand pumice soils were planted into the forest (Fig. 2.34).

The mystery of "bush sickness" was unraveled by scientists who found that the bush sickness was caused by a deficiency of cobalt which can be remedied by adding cobalt to fertilizer or giving stock vitamin B12. With a growing demand for dairy products, some of the plantation forest areas are being converted to dairy farms once the trees have been harvested.

Fig. 2.34 The Kaingaroa Forest—the largest plantation forest in the Southern Hemisphere—was planted in soils formed on rhyolite pumice in the 1930s. The soils were then considered useless for pastoral farming as animals became ill with “bush sickness”

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