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Landforms of the World with Google Earth

Understanding our Environment

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Cover image: A beautiful syncline in the Andes of NW Argentina, exposing Jurassic rock formations. Large-scale erosion accompanying the uplift during the Andean orogeny has removed the adjacent (anticline) parts of these rock formations, but the trough-like syncline persisted. Picture-perfect cuestas have developed towards the center of the structure, where inclined layers of sedimentary rocks of different colour are incised by draining channels (Image credit: ©Google earth 2012).

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Preface

Scientific outreach and a passion for the power of observation of the physical world around us are at the heart of this book. From the extraordinary observational skills harnessed by the first scientific travelers in antiquity, to the naturalists and explorers of the eighteenth and nineteenth century like Alexander von Humboldt or Charles Darwin, and through to the modern day, scientists have been the driving force for revolutionary discoveries in the field of earth and environmental sciences. Today, we can observe the surface of the earth when travelling by airplane to every corner of the globe within days or hours, or use virtual globes in the public sphere that are becoming popular and powerful tools to visualize data and information in a geographical context over the ever broadening range of influence of the internet. The patterns, forms and geometries that we can visit with our desktop journey are often of astonishing beauty and staggering aesthetic harmony for the human eye. Besides igniting our scientific quest to understand their origins, they impress us in many psychological and emotional ways as they have impressed artists from all disciplines, painters, sculptors or musicians, over the long time of human history. The exquisite interrelation between arts and sciences and a homage to the power of observation and precise measurements resonates within the words of Alexander van Humboldt: *“Nature herself is sublimely eloquent. The stars as they sparkle in firmament fill us with delight and ecstasy, and yet they all move in orbit marked out with mathematical precision”* (In: “Narrative of Travels of the Equinoctial Regions of the New Continent during Years 1799–1804”, London [1814], Vol. 1, pp. 34–35).

Google Earth images showcase the astonishing diversity of the landforms of the world and are the travel tickets to guide the reader along a geomorphologic journey to typical and spectacular landforms in diverse environments on all continents. Google Earth’s bird’s eye perspective is enriched with photographic images and graphic illustrations and aims to familiarize the reader with diverse terrestrial environments and landforms and the processes that shape them by providing short interpreting texts based on the extensive field experience of the authors. This volume is thought as an inductive addition to existing textbooks on geomorphology, using a language which intends to be understandable for everyone. As the subtitle of our book, “Understanding our Environment” says, we try to provide insights into the diversity of terrestrial landforms especially to young students and scientists and to motivate the interested public to actively observe the landforms and related processes. Part I (Introduction) introduces the reader to the scientific discipline of geomorphology, Part II and III explore the forms of the Earth’s surface and the driving forces and processes of nature that result in the landscape and scenery around us. The epilogue touches on the human species as a geologic force in forming and changing the natural environment. Selected short reference lists at the end of each chapter will offer the reader easy access to additional background material that covers the recent progress in the specific topic. An index listing regional and general keywords allows quick searches to special chapters, terms and geographic features.

We thank Google Earth for the permission to use their imagery and are indebted to our editors at Springer Publishing, Petra van Steenbergen and Hermine Vloemans, for their superb support, Frank Schmidt-Kelletat for graphical and technical assistance, and Anne Hager for her support with control and formatting.

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About Google Earth

Virtual, web-based globes such as Google Earth, NASA World Wind or Microsoft Virtual Earth allow all of us to become travelers visiting the most remote places, and tour our planet or even outer space at speeds faster than a rocket. Any computer user can easily, at no charge, download and use Google Earth (for both PC and Mac computers).

If you have not done so already, download Google Earth (the new version) from earth.google.com. Install it on your computer and prepare yourself to fly around the globe on your own research expedition. You can travel to millions of locations and look for the context of all landscape features of interest to you (e.g., geography, geology, vegetation, man-made structures and more). You can also see these objects from different altitudes (i.e., in different scales), perspectives and directions; you can view a chosen area around 360° from an arbitrary point in the air; and you can fly deep into canyons and craters. You can look straight down in a traditional 2D perspective or enable an oblique view in 3D and you can hover above one location, circle around or fly like a bird over countries, continents and oceans. In this book we focus on geologic and geographic features, but that is only a snapshot of what Google Earth is providing with their virtual globe. There is no room here for a complete tutorial, but you will find that the program is so easy to use and understand that you will become an expert after working with it for a few minutes. Please visit the Google Earth webpage for a complete free Google Earth tutorial that is constantly updated to reflect the improvements in different versions of Google Earth (http://earth.google.com/support/bin/answer.py?hl=en&answer=176576).

We hope that the diversity of the landforms of the world will come alive for you and stimulate your curiosity to become an explorer of these fascinating places either as a hobby or profession.

Contents

Part I

Introduction

1 Shaping the Surface of Earth: Geomorphology in a Nutshell

Abstract

Landscapes are shaped by the uplift, deformation and breakdown of bedrock and the erosion, transport and deposition of sediment in a constant cycle of change that operate since the early stages of the formation of our home planet over four billion years ago. The forces of nature that drive these changes originate from processes operating within the Earth's interior or are related to the four inter-connected "geospheres" that comprise the area near the surface of the Earth: the lithosphere, hydrosphere, biosphere, and atmosphere. Every now and then, objects from outer space leave behind their imprints in form of impact craters in the landscape and remind us that Earth is part of the great wonders of the universe. As scientists love to categorize, geomorphologists are not an exemption: We classify landforms as destructive or constructive depending on the forming processes involved. The first chapters introduce the reader to the concepts of geomorphology in a nutshell and explain the forming processes that shape and sculpture our landscape or are unique for our home planet.

The scientific endeavor to understand the nature and history of the forms and the processes sculpturing the surface of the Earth (and other planets) is termed "geomorphology". Terrestrial geomorphology in particular explores the forms and the processes operating upon Earth's landmasses that cover about 30 % of our globe or more than 150 million km^2 as continents and islands. Geomorphologists approach research questions within the rational, empirical and analytical traditions of modern science. This includes observations and information gathering in the field and hypotheses testing in laboratory or field settings or computer modelling. Efforts are taken to replicate and to generalize results. As any other scientists, geomorphologists aim to develop a fundamental framework (or classification scheme) that allows categorizing a certain geomorphic unit of a landscape based on:

- its general structure and shape (*landform*),
- its origin and development (*process*) – geomorphic process types are tectonic, volcanic, gravitational or mass wasting, fluvial, glacial, periglacial, solution, aeolian, or lacustrine and coastal,
- the measurements of its dimensions and characteristics (*morphometry*) such as relief, elevation, aspect, slope gradient, landform width, microfeature relief, dissection frequency or depth, drainage pattern, drainage density and stream frequency,
- and, the presence and status of process overprinting (*geomorphic generation*).

The concept of geomorphic generation incorporates the dimension of time as many forms may have been shaped by different processes over geologic time scales and therefore may have a multi-genetic character. Think of the fjords in Norway or southern New Zealand. The majestic, steep rock faces exhibit rocks that may be hundreds of millions of years old, but the form itself has been initially carved out by surface water in creeks and streams as a fluvial valley several million years ago. Crushing and grinding glaciers transformed these landforms in the typical glacial U-shaped valleys during several glacial periods over the last two million years of the Quaternary and were replaced by fluvial erosion during the warmer climate periods and subsequent marine inundation.

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The geomorphic process types can be classified as endogenic or exogenic. Endogenic processes are driven by forces operating in the Earth's interior like mantle convection, plate tectonics, volcanism or earthquakes. These processes leave their footprint in the landscape as endogenic or structural landforms; examples are mountain belts, volcanoes, faults or folds. Exogenic process types operate on or near the surface of the Earth and are associated with one of the four geospheres – the lithosphere, the hydrosphere, the biosphere and the atmosphere. They result in sculptural landforms that are shaped by water, ice and wind (the most important ones) and also life in the widest sense. Biota has a profound influence on weathering and erosion processes and thus is also significant in landscape evolution. Of course, endogenic landforms are under the constant influence of exogenic processes and are shaped and modified by the geomorphic forming agents that govern the past and present environmental conditions.

To us, the joy and inspiration of geomorphology are nurtured by the multitude of possible forming parameters and the detective challenge to unravel the history and evolution of a landscape that we cherish today for its beauty, uniqueness, and intrinsic value or importance as geologic heritage. Each reader can easily comprehend that any landform or topography will depend on a wide variety of environmental parameters – the tectonic and geographical position and associated climatic regimes, the geology in terms of different rock types and the stability of forming conditions over different time scales. Another line of inquiry is whether the landform is an expression of processes operating today as an active dune in the Sahara or whether it is a result of processes operating in the past like the U-shaped valleys as remnants of a glacial world, dry river beds or inactive volcanoes.

The selected Google Earth images in this volume aim to communicate the diversity of geomorphology by presenting a variety of examples for landforms of similar forming conditions. The volume explores this order of process types and starts in Part II with a virtual visit to a wide diversity of endogenic forms originating from processes in the Earth's asthenosphere. Landforms or geological formations that are related to magmatic processes such as volcanism or intrusions of molten rock into the surrounding bedrock are topics in Chaps. 2 and 3. Tectonic processes and their expression as landforms are visualized in Chaps. 4 and II.4. Astonishing as it may sound, the tectonic processes beneath the surface of the Earth have governed the planet's 4.5 billion year evolution and our position in the solar system, where we circle our home star, the Sun, at an average distance of 150 million km, make our Earth unique within the solar system: Earth has a solid surface, an atmosphere in which we can breathe and liquid water we can drink. These three properties allow life, as we know it, to exist.

Plate tectonics are the driving mechanism for the changing geography and steady renewal of the Earth's surface. The outer, solid surface of the Earth is divided into tectonic plates composed of lithosphere, which drifts on top of a 2,900 km-thick mantle, and is constantly moving towards, away from or past each other (Figs. 1.1 and 1.2a, b). The lithosphere is comprised of the Earth's crust, which has a variable thickness of 35–70 km under continents and 5–10 km in ocean basins, and the rigid portion of the upper mantle. The Earth's mantle stores most of the internal heat of the Earth. Flow or convection processes are driven by both thermal and chemical heterogeneities within the mantle. Convection processes in the mantle lead to the formation of volcanic spreading centers under Earth's oceanic crust that stretch across thousands of kilometers through all major ocean basins, i.e. in the form of sea floor spreading along mid-ocean ridges. Here, the continental plates move away from these volcanic spreading centers like conveyor belts and earth scientists term this process plate divergence (Figs. 1.1, 1.2, 1.3, 1.4 and 1.5). The oceanic plates then sink back into the mantle along subduction zones such as off South America or Japan – places where immense geologic forces are evident in the form of earthquakes, mountain building and active volcanoes (e.g., the South American Andes or the Japanese Alps). Around the subduction zones of the Pacific Plate is a region often referred to as the Ring of Fire. It accounts for about 90 % of the world's earthquakes (and 81 % of the world's largest; Fig. 1.2a) and is home to over 75 % of the world's active and dormant volcanoes.

Despite the constant geologic renewal throughout the evolution of the Earth, some landforms or features have a very long history and may have maintained their form and/or position for millions of years. The Finke River in the Northern Territory of the Australian continent is a good example. It is one of the oldest rivers in the world and represents a remnant of a drainage pattern which was active before the Australian plate separated from the Antarctic plate. Australia began its tectonic journey across the surface of the Earth heading north as an isolated continent since ~55 million years ago, and continues to move north by about 7 cm each year. Landforms created by impact craters can be even dated back to more than two billion years of age.

Plate motions are not always smooth. Instead they exaggerate stress along the lithospheric plate boundaries and often plates are stuck together at the edges while the rest of the plates continue to move. As a result, the rocks along the plate boundaries are distorted or what earth scientists call "strained". As the motion continues, the strain builds up to the point where the rock cannot withstand any more bending and breaks. The sudden release of energy in the Earth's crust creates seismic waves that radiate outwards from the rupture and we experience a shaking of the ground – an earthquake. Most earthquakes occur on the boundaries between plates, where one plate is forced under another, in areas off island chains such as Japan, Indonesia or the Solomon Islands, or past another as occurs in California and New Zealand.

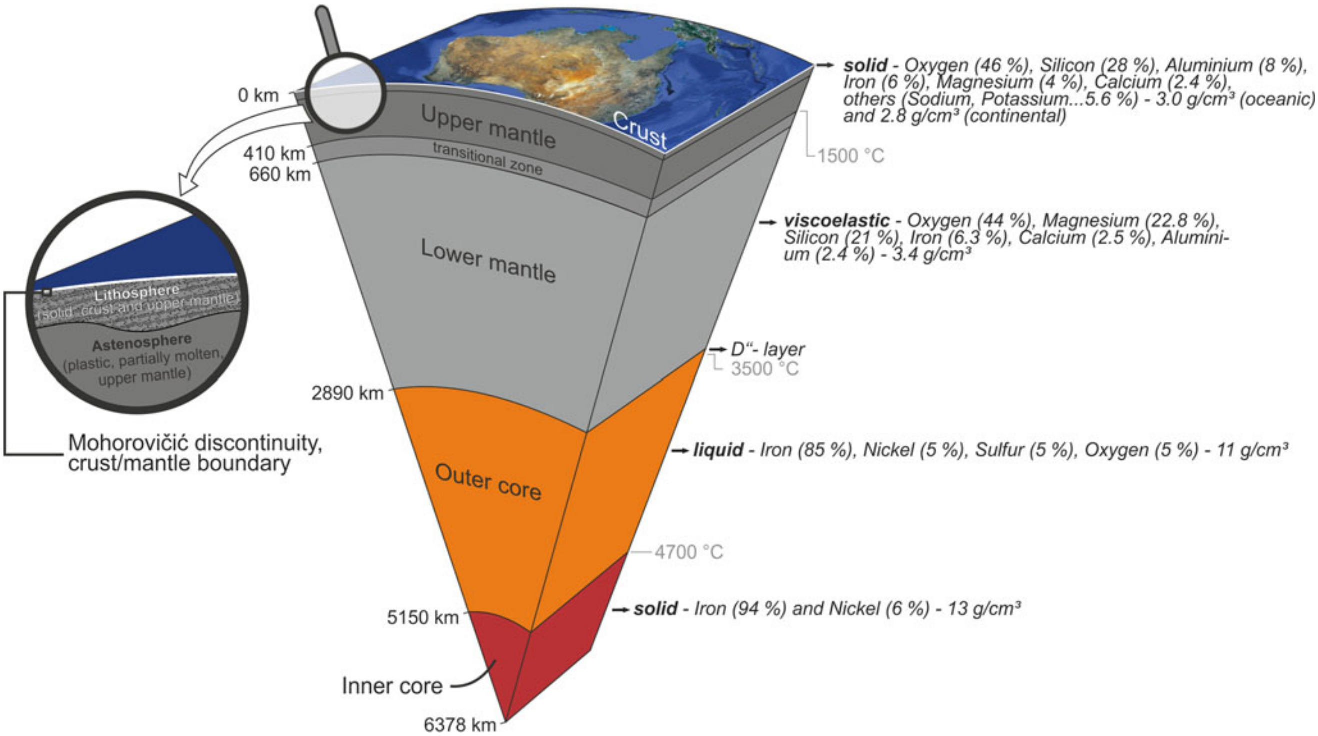

Fig. 1.1 The Earth's interior is composed of four layers, three solid and one liquid (the outer core). The inner core is composed of iron and nickel and temperatures are estimated between 5,000 and 7,000 °C – almost as hot as the surface of the sun. For comparison, the melting point of steel is around 1,500 °C (Image credit: S.M. May, based on Grotzinger et al. 2006)

Earthquakes and long-term tectonic processes can have a visible expression as a feature in the landscape (Fig. 1.7a, b) or at infrastructure level (Fig. 1.8a–c).

Part III opens with a chapter on objects from outer space that leave their imprints in the landscape as extra-terrestrial impact structures. We return to more earthly exogenic matters with the question where landscape materials come from and look at physical and chemical weathering processes. But how do landscape materials get down from mountaintops to valley floors? Gravitational processes or the simple geomorphic transport law "What goes up, must come down" are illustrated in Chap. 8. Planet Earth has a large mass and as a consequence exaggerates significant gravitation on all objects. Any landscape with a topographic gradient will result in the transportation of any material directed downhill, either as mass movements or within a medium such as water or ice. Mass wasting is the geomorphic process by which surface material (soil, unconsolidated sediment, rock) move downslope under the influence of gravity. The movement can occur over different timescales, such as a sudden event that take place within seconds (rockfalls or landslides) or a gradual event that takes years (soil creep).

By far the largest group of landforms is connected to a property of our planet that makes our home in the universe so unique (as far as we know): the existence of liquid water. Fluvial valleys carved by running streams or rivers come in an astonishing variety of sizes, cross profiles or configurations along a river course. Examples for the erosive force of water and the results of accumulation and sedimentation as constructive processes exemplified by alluvial fans and terraces are compiled in Chap. 9. One of the more ordinary "plain" groups of forms in geomorphology (compared to dwindling mountains and gorgeous river gorges) are the plains which are the topic of Chap. 10. As destructive forms (compared to sediment infill of depressions) they are called *peneplains* meaning "nearly flat", as they often are the home of residual single mountains that are consequently called *inselbergs*. The low and featureless slopes along the foothills of mountains and mountain chains are termed *pediments* that translate to "plains at the foot [of mountains]", or *glacis* derived from the cleared area around old fortifications that have been constructed to see any approaching enemy. Wind as a landscape sculptor and its extensive group of landforms and features are illustrated in Chap. 11. The most powerful geomorphic force is associated with glaciers. The weight and movement of these ice masses shape sharp mountain peaks, carve steep U-shaped valleys, whale-shaped bedrock hills and fjords and deposit thick blankets of sediment (gravels or sand) in lowlands and valleys. Glaciers themselves are part of the Earth's surface and they are described visually with all their morphological characteristics in Chap. 12. Landscapes

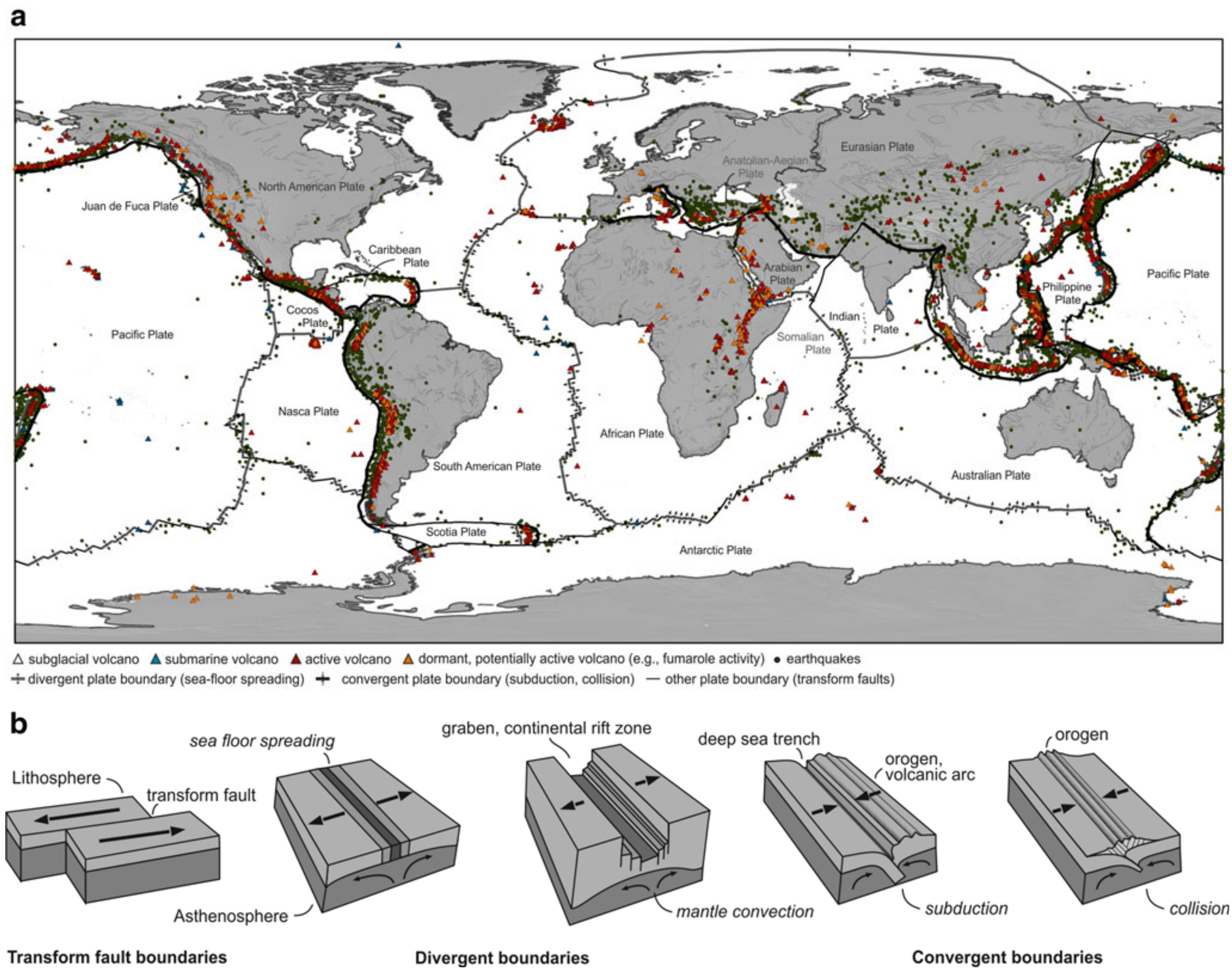

Fig. 1.2 (**a**) The main tectonic plates of the Earth's lithosphere with the three different types of plate boundaries – divergent, convergent and transform boundaries where plates move lateral to each other. The world map shows the distribution of active and potentially active volcanoes. About 80 % are found at boundaries where plates collide, 15 % where plates separate, and the remaining few at intraplate hot spots. Not shown on this map are the numerous volcanoes of the mid–ocean ridge system below the ocean's surface where in fact most of the lava is erupted on Earth's surface (Image credit: S.M. May; based on USGS data and Grotzinger et al. 2006). (**b**) Schematic illustration of different plate boundaries – transform faults or transform plate boundaries, where tectonic plates move laterally along each other; divergent plate boundaries, where new oceanic crust is formed by sea floor spreading or graben and rift structures develop on continents; convergent plate boundaries, where subduction of oceanic lithosphere below oceanic or continental lithosphere or collision of two continental lithospheric plates takes place (Image credit: S.M. May; adapted from Grotzinger et al. 2006)

that depict forms associated with colder climates (permafrost regions) are the focus of Chap. 13.

In Part IV we end our tour through the non-living parts of our environment and briefly look as our own species as a geologic force as can be detected from space in the epilogue. Explanations of the different forming processes are given as introductory remarks (in a nutshell) for the individual chapters.

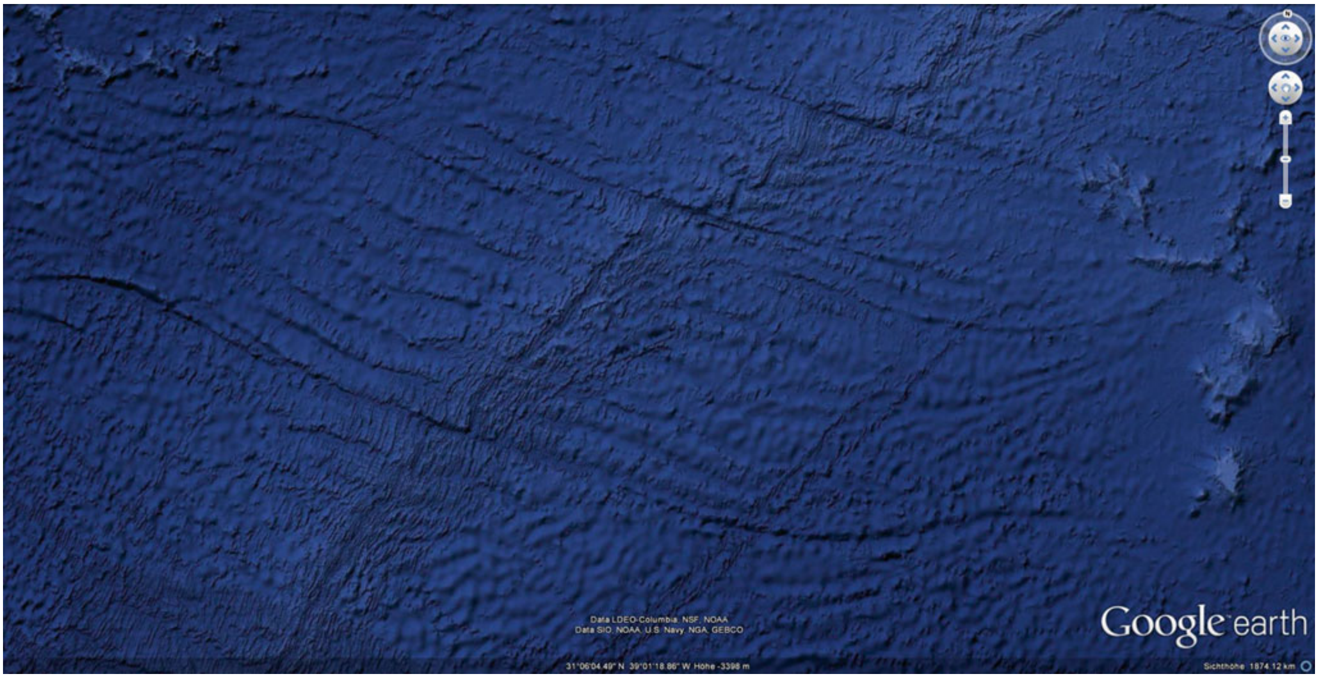

Fig. 1.3 Sea floor spreading along the Mid-Atlantic Ridge generates new oceanic crust: the rigid lithosphere drifts as plates on the asthenosphere. At the line of spreading, a submarine mountain ridge is created, stretching from southwest to northeast in this image. The W-E running transform faults offset the spreading centers of the Mid-Atlantic Ridge, resulting in a step-like appearance. Width of image is ~2200 km. (Image credit: ©Google earth 2012)

a

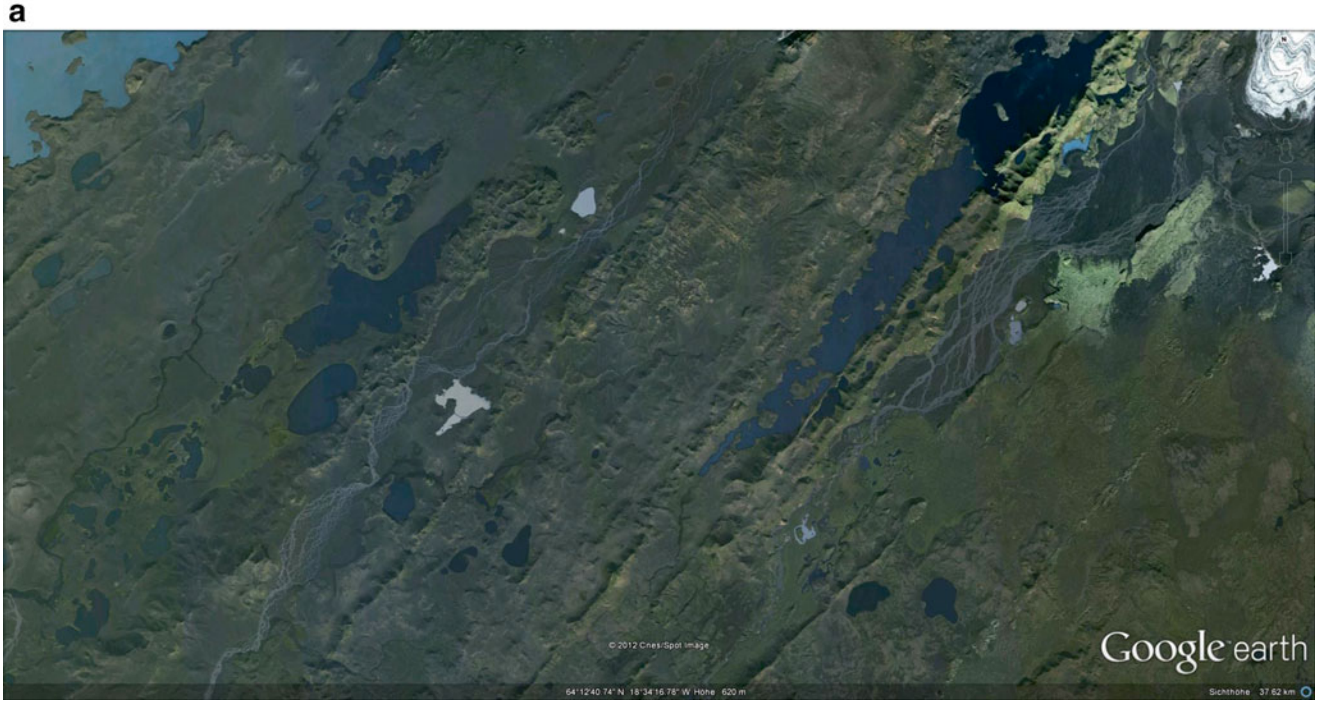

Fig. 1.4 (**a**, **b**) The Mid-Atlantic Ridge is a divergent plate boundary that surfaces above sea level in Iceland, making the rifting process easily visible from space (Image credit: ©Google earth 2012); (**c**) Simple measurement instruments like this metal bar were used to help to estimate the rate of divergence before the era of sophisticated GPS techniques. Iceland has 30 active volcanic systems, of which 13 have erupted since the colonization of Iceland in 874 AD – the last major eruption was by the active volcano Grímsvötn in May 2011 and caused major disruptions in European air traffic (Image credit: D. Kelletat)

b

c

Fig. 1.4 (continued)

Fig. 1.5 Excellent examples of active spreading centers are the Red Sea and the Gulf of Suez (*upper left*) and of Aqaba (*upper right*). The Red Sea is a young ocean that is forming where Arabia is separating and moving away from Africa. From the southern tip of the Red Sea southward through Eritrea, Ethiopia, Kenya, Tanzania and Mozambique, the African continent is rifting or splitting apart along a zone called the East African Rift. This spectacular geologic event that gives birth to a new ocean will be complete when saltwater from the Red Sea floods the massive rift, probably in several million years from now. The Gulf of Aqaba is continuing in the Dead Sea and the Jordan graben to the north. You may also fly with Google Earth to other spreading zones, such as the Gulf of Baja California in northwest Mexico (Image credit: ©Google earth 2012)

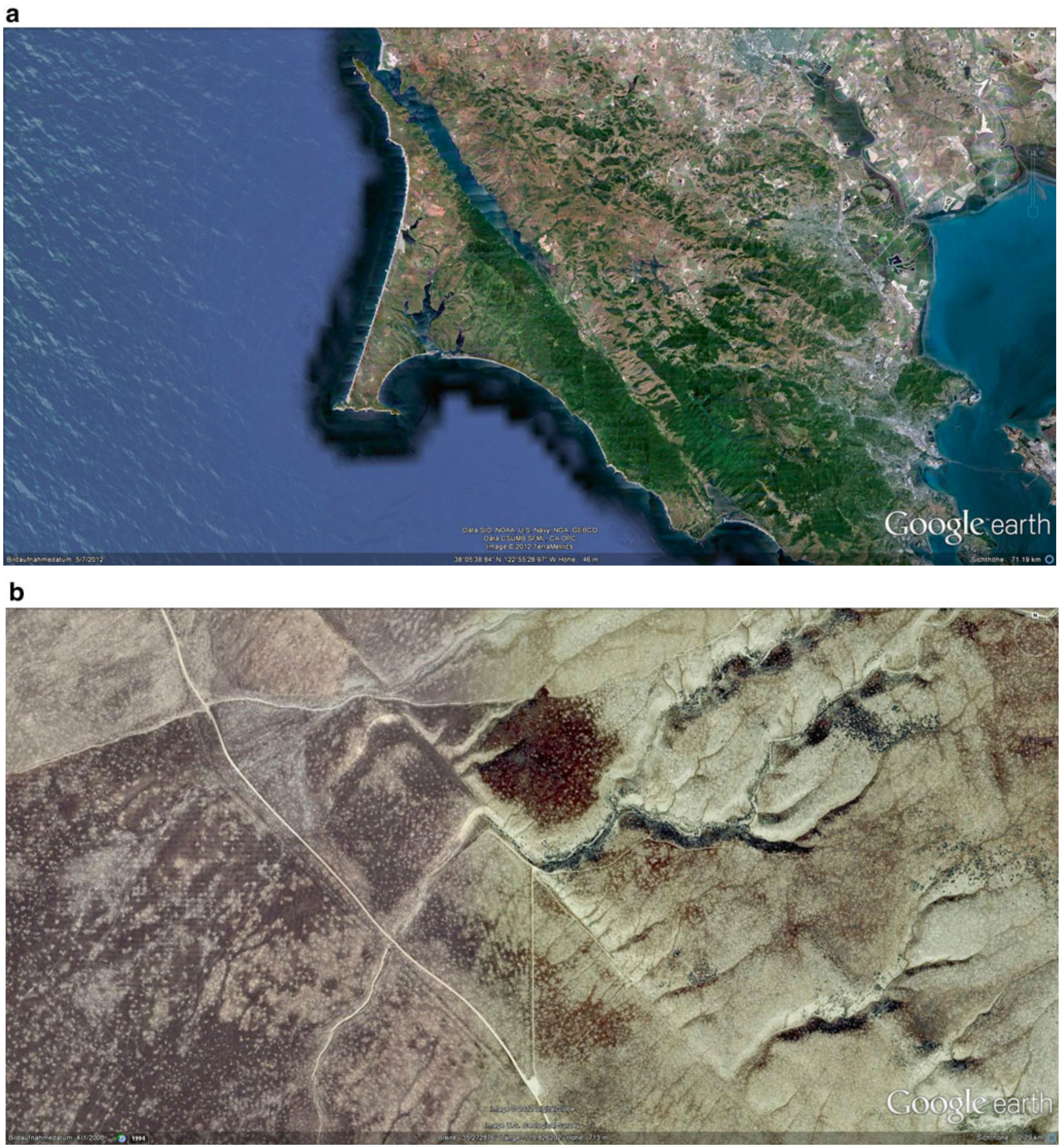

Fig. 1.6 (**a**) The transform boundary along the San Andreas Fault in California (USA) is visible as the straight coastline at Point Reyes National Seashore. It is associated with high seismic activity that produces strong earthquakes such as the San Francisco earthquakes in 1906 and 1989. Riverbeds were shifted for about 150 m (**b**), and even 350 m (**c**) in central California (Image credit: ©Google earth 2012)

c

Fig. 1.6 (continued)

a

Fig. 1.7 (**a**) During the Montenegro or Skopje earthquake in 1963, the bushes shifted for 5 m while a 3 m deep graben formed at the surface. The pasture in the background has been uplifted for nearly 1 m (Image credit: D. Kelletat). (**b**) Over longer geologic time scales, the release of tectonic stress may leave distinct signatures on the landscape such as this 14 km long graben-like structure at the Colorado Plateau (*35°44'N* and *111°40´W*; Image credit: ©Google earth 2012)

b

Fig. 1.7 (continued)

a b

Fig. 1.8 (**a**) A staircase in the Minoan settlement (>3,500 years) of Akrotiri on the island of Santorini/Thira (Aegean Sea, Greece) has been destroyed by compression forces during an earthquake in early historical times. (**b**) Sideward displacement of the mayor's house in the medieval township of Venzone (northeast Italy) during an earthquake 50 years ago. The small roof tower stayed almost at its old place.

c

Fig. 1.8 (continued) (**c**) In the Nabataean town of Petra (Jordan), the columns of a 2,000-year-old temple have collapsed and are resting in a nice imbricated pattern. The seismic event occurred west of the location (left side of the picture) where the main graben structure of the Dead Sea is situated (Image credit: D. Kelletat)

Reference

Grotzinger J, Jordan TH, Press F, Siever R (2006) Understanding earth, 5th edn. Macmillan, Palgrave

Part II

Endogenic Forms and Processes

2 Volcanic Landforms

Abstract

Our early ancestors were just spreading out of Africa and east across Asia when one of the most explosive volcanic eruptions on Earth in the last two million years took place at 73,880 years ago (with a margin of error of just a few centuries) in northern Sumatra. The scientific team who dated the event works on the hypothesis that the Toba eruption played a role in shaping human interactions, extinctions and dispersals in Asia and Australia, and has left a legacy of the eruption in our genes. Ancient philosophers were also awed by volcanoes and their fearsome eruptions of molten rock. In their efforts to explain volcanoes, they spun myths about a hot, hellish underworld below Earth's surface and in early Christian society, the idea remained that volcanoes were the gateway to hell. In Roman mythology, Vulcan was the god of fire, volcanic eruptions, and the hearth and forge. He was the gods' blacksmith, making arrows and shields for the deities and whenever a mountain erupted, it was said to be Vulcan pounding on his anvil. The god's legacy remains as the modern name *volcano* is derived from the Latin name "*Vulcanus*", and today means all mountains or hills that are built by lava and other erupted material. But volcanoes do not just occur anywhere, as we shall soon see.

Basically, our ancestors from different cultural traditions around the world had the right idea about Earth getting hotter with depth and that under the surface, the Earth's interior is hot and molten. Today scientists agree that the earth is hot inside due to three main sources of heat in the deep earth: (1) heat from when the planet formed and accreted, which has not yet been lost; (2) frictional heating, caused by denser core material sinking to the center of the planet; and (3) heat from the decay of radioactive elements. Taking the temperature of the inside Earth is made possible by some amazing science and engineering: Over 40 years ago, researchers in the then Soviet Union began an ambitious drilling project, the Kola Superdeep Borehole, whose goal was to penetrate the Earth's upper crust down to 15,000 m. In 1989, a depth of 12,262 m was reached, but the temperatures of 180 °C at this depth and location were much higher than the 100 °C expected by the drilling team. As a consequence drilling deeper was deemed unfeasible and the drilling was stopped in 1992. The temperature profile of the Earth's interior – the geothermal gradient – shows that on average temperatures increase for 3.5 °C per 100 m, but under normal conditions the geothermal gradient is not high enough to melt rocks, and thus with the exception of the outer core, most of the Earth is solid.

Therefore, magmas form only under special geologic settings and consequently volcanoes are only found on the Earth's surface in areas above where these settings occur: To generate magma in the solid part of the Earth either the geothermal gradient must be raised in some way or the melting temperature of the rocks must be lowered. The geothermal gradient can be raised where hot mantle material rises to lower pressure or shallower depth, carrying its heat with it as occurs beneath oceanic ridges, at hot spots, and beneath continental rift valleys. Lowering the melting temperature to partially melt the surrounding rocks and generate magma can be achieved by adding water or carbon dioxide (flux melting) at places deep in the Earth, where the temperature is already high, like subduction zones. Here, water present in the pore spaces of the subducting ocean floor or water present in minerals like hornblende, biotite, or clay minerals

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would be released by the rising temperature and move into the overlying mantle section to generate magmas.

Magmas are less dense than the rocks that produced them and therefore, as they accumulate, begin to rise upward through the lithosphere. In some places, the melt may find a path to the surface by fracturing the lithosphere along zones of weakness. In other places, the rising magma melts its way toward the surface where we call it lava. The accumulation of lava and other erupted materials as a hill or mountain is called a volcano.

Before the acceptance of Alfred Wegener's plate tectonics theory by the scientific community in 1967, cartographers charted the deep ocean trenches, seismologists plotted earthquakes beneath the trenches, and volcanologists studied the distribution of volcanoes and noted a concentration of volcanoes around the rim of the Pacific Ocean and nicknamed it the Ring of Fire (see Fig. 1.2). Today, the concept of plate tectonics can explain essentially all major features in the global pattern of volcanism such as the observation why so many of the world's volcanoes are situated around the plate boundaries surrounding the Pacific Ocean, where oceanic plates are being subducted beneath the Earth's continental crust. The explanation of the Ring of Fire in terms of plate tectonics and subduction processes was one of the great successes of Wegener's revolutionary theory of continental drift from 1912, although it took nearly half a century to finally convince fellow scientists that Alfred Wegener and later Arthur Holmes were on to something so significant with their theory of plate tectonics that today (another half a century later) is almost regarded as common knowledge by the public.

A world map (Fig. 1.2) shows the distribution of active volcanoes with vents on land or above the ocean surface with the majority occurring in tectonic settings where plates collide (about 80 %) and oceanic lithosphere is subsiding beneath oceanic or continental lithosphere back into the asthenosphere. The remaining volcanoes are found at diverging plate boundaries or occur within plate interiors (Fig. 1.2).

Subduction zone volcanism occurs where two lithospheric plates are converging and one plate containing oceanic lithosphere descends beneath the opposing oceanic or continental plate into the earth's mantle. The lithospheric crust of the subducting plate contains a significant amount of surface water, as well as water contained in hydrated minerals within the basalt of the sea floor. As the subducting slab descends into the Earth's interior, it progressively encounters greater temperatures and greater pressures that cause the descending slab to release water into the overlying mantle wedge. Water has the effect of lowering the melting temperature of the mantle, thus causing it to melt and produce magma that rises upward to produce a linear belt of volcanoes parallel to the oceanic trench. If the oceanic lithosphere subducts beneath another oceanic lithosphere, a chain of volcanoes is forming which contributes to the formation of an oceanic island arc.

Fig. 2.1 The so-called Toba 'super-eruption' created Lake Toba, Earth's largest Quaternary caldera about 100 km long, 30 km wide and 500 m deep is easy to spot with Google Earth in the center of the image. It is estimated that more than seven trillion tons of volcanic materials were ejected, of which at least 800 km^3 was spread as ash across the Indian Ocean and the adjacent landmasses of south and southeast Asia, covering several million square kilometers of the planet's surface in debris (Storeya et al. 2012) (Image credit: ©Google earth 2012)

Modern examples are the Aleutian or Kuril Islands, the Philippine Islands and the Japanese Archipelago (Fig. 2.2a). If the oceanic lithosphere subducts beneath continental lithosphere, then a similar parallel belt of volcanoes will be generated on the continental crust. We call this a volcanic arc and good examples can be found around the Pacific Ring of Fire including the Cascade volcanic arc of the western USA and Canada and the Andes volcanic arc of South America.

Another birthplace of volcanoes is the spreading centers of the Earth's crust, along the mid-ocean ridges (Fig. 2.2b). Most of the lava at Earth's surface that is erupting along these diverging plate boundaries are submarine. Only at certain places we can witness this spectacular geologic event where the spreading centers are surfacing above the ocean such as the volcanic island of Iceland (Fig. 2.2b), or along the graben and rift zone of eastern Africa (Ethiopia, Kenya, Tanzania with the majestic volcanoes of Mt. Kilimanjaro or Mt. Kenya).

Volcanoes may also exist far away from any plate boundaries and geologists struggled very much to explain their existence. Then in 1963, J. Tuzo Wilson, a Canadian geophysicist, provided an ingenious explanation within the framework of the newly accepted plate tectonics theory by proposing the "Hot Spot" or Mantle Plume Hypothesis as we call it today: At some places on Earth, hot magma rises in confined, narrow jets from deep within the Earth's mantle, penetrates the lithosphere and erupts on Earth's surface. These volcanically active hot spots are often visualized as blowtorches anchored in Earth's mantle and are stationary relative to each other. On their epic geologic journey, the lithospheric plates may move over hot spots with the current position of a plate over a hot spot marked by an active volcano. As the plate moves away, the volcano stops erupting and a new one is formed in its place – an island chain is forming. With time, the volcanoes keep drifting away and progressively become older, extinct and eroded. As they age, the crust upon which they sit cools and subsides, and in combination with erosion they eventually submerge below sea level.

The Hawaii Island Archipelago owes its existence to such a hot spot (Fig. 2.3a–c): The main Hawaiian Islands which make up the state of Hawaii (Hawaii, Maui, Oahu, Kahoolawe, Lanai, Molokai, Kauai and Niihau) are the peaks of undersea shield volcanoes that formed at the Hawaiian hotspot, which is presently located under the Big Island of Hawaii. Dating of the volcanoes on each island yields a rate of plate movement of the Pacific Plate westwards over the hot spot of about 10 cm/year with the oldest island above sea level, Niihau (5.5 million years), at the north-western extent of the chain. The outer Hawaiian

a

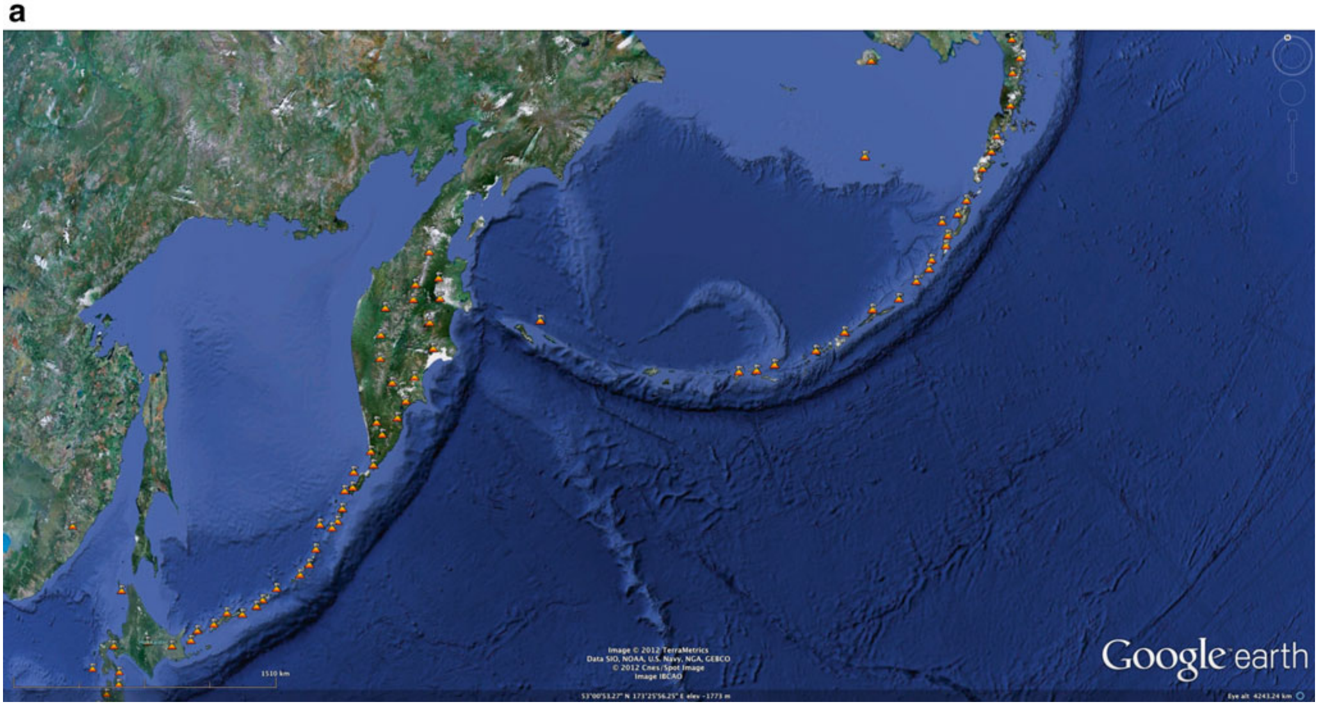

Fig. 2.2 (**a**) You can see the over 450 volcanoes that make up the Ring of Fire from space, running in a straight line or side by side around the edges of the Pacific Ocean or dominating island chains like Japan, the Philippines or Indonesia. (**b**) The Mid-Atlantic Ridge, one of the Earth's spreading zones (mid-ocean ridges) stretches from north to south across the entire Atlantic Ocean. It surfaces at Iceland, where high volcanic and tectonic activity (such as graben structures, see Chaps. 1 and 4) manifest the divergence of lithospheric plates (Image credit: ©Google earth 2012)

b

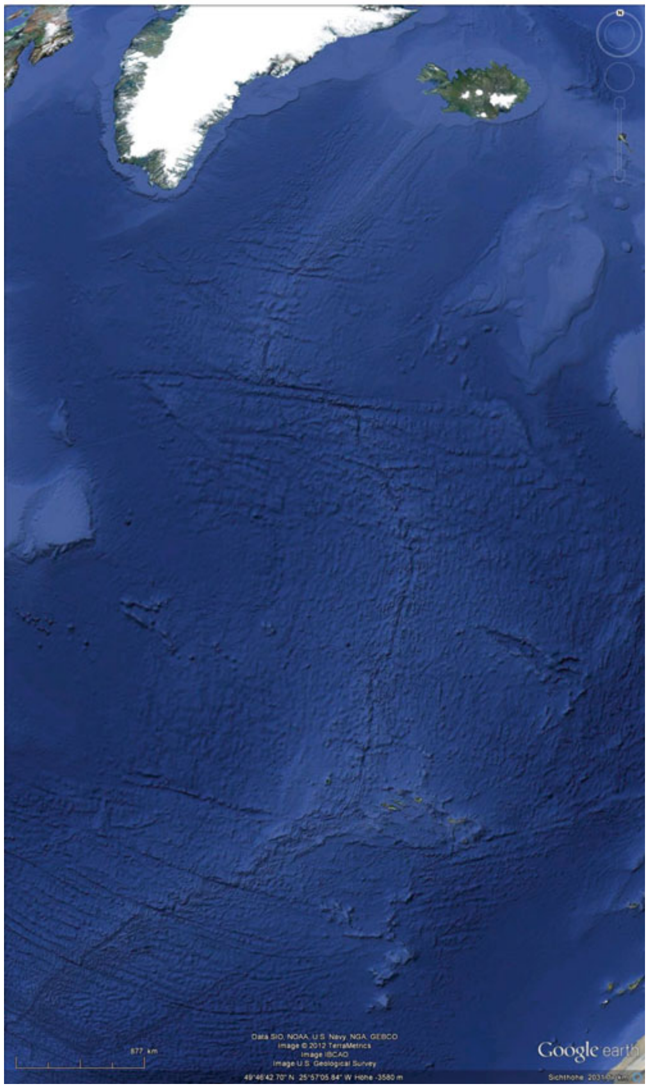

Fig. 2.2 (continued)

Islands are a series of nine smaller, older eroded islands north of Kauai that extend from Nihoa to Kure and represent the above sea level remnants of once much larger volcanic mountains. Even beyond Kure the Hawaiian island chain continues as a series of now-submerged former islands known collectively as the Emperor seamounts (Fig. 2.4).

The endless battle between the forces of nature – creation of new land and destruction by terrestrial erosion and marine abrasion – is very prominent in Polynesian mythology. In Polynesian pre-European mythology, Pele is the fire goddess of Hawaii who was both revered and feared. She is often depicted as tempestuous and destructive, yet beautiful deity, and is said to live in the crater of the volcano of Kilauea on the big island of Hawaii. She could cause earthquakes by stamping her feet and volcanic eruptions and fiery devastations by digging with the Pa'oe, her magic stick. An oft-told legend describes the long and bitter quarrel between Pele and her older sister Namakaokahai, Goddess of the Sea that led to the creation of the Hawaii's volcanic island chain. Tahiti, at the south-eastern end of the Society Islands and the Galápagos Islands are other examples of intraplate volcanism (Fig. 2.5).

2.1 Volcanic Products

The different types and shapes of volcanoes as a landform depend mainly on the chemical composition and the gas content of the magma as it rises through the lithosphere (or lava as it emerges on the land surface) and the rate on which lava is produced, which in turn are principally determined by geologic processes in different plate tectonics settings.

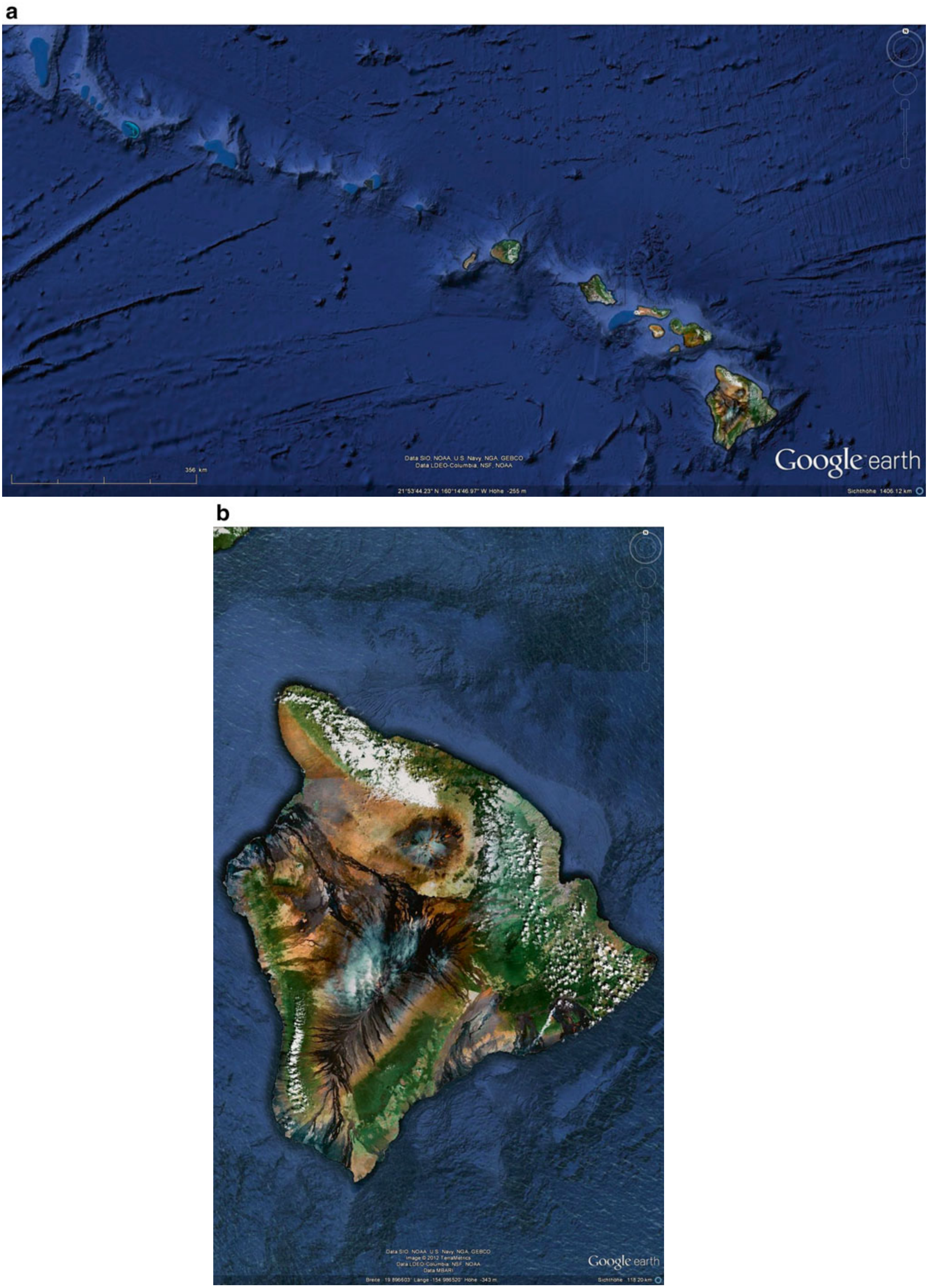

Fig. 2.3 (**a**) The volcanic island chain of Hawaii in the Pacific Ocean is the result of hot spot volcanism. (**b**) The largest and highest island, Big Hawaii, is constructed of five major volcanoes: Kilauea, Mauna Loa, Mauna Kea, Hualalai and Kohala. Mauna Loa is the largest active volcano on Earth while Kilauea is presently one of the most productive volcanoes on Earth in terms of how much lava it erupts each year

c

Fig. 2.3 (continued) The youngest volcano, Loihi, is rising steadily from the ocean floor south of Big Island. At present, its summit is 160 m below sea level, but occasionally boiling water and steam clouds makes a spectacular statement about its existence (Image credit: ©Google earth 2012). (**c**) Hawaiian volcanoes primarily erupt a type of lava known as basalt. Basaltic lava is extremely fluid and can flow downhill relatively fast and far, which is why the Hawaiian shield volcanoes generally have gentle sloping sides (Image credit: D. Kelletat)

Fig. 2.4 Google Earth reveals the topography of the Pacific Ocean seafloor and the location of the immense Hawaiian Ridge-Emperor Seamount Chain (Image credit: ©Google earth 2012)