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978-1-108-47623-2 — Plate Tectonics
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Introduction to a Tectonically Unique Planet

Even though many important geological processes are almost incomprehensibly slow, our planet is far from boring. Volcano eruptions and earthquakes are perhaps the best examples of dramatic and sometimes life-threatening incidences that quickly make news headlines. Climate variations and sea-level changes are also in the news, even though these are slower. Plate motions, such as the ~2 cm yearly increase in distance between London and New York, generally go unnoticed by the media but not by geoscientists. Most of these fascinating observations are related, and the plate tectonic model is the model that best explains the relationship between different types of plate boundaries, volcanism, seismicity, topography, crustal thickness, the distribution of different types of deformation structures, the cycling of volatiles, the evolution of life, the distribution of species through time, and much more. Even features that appear to be independent of plate tectonics can be added if we also consider the gravity and thermally controlled dynamics of the sub-lithospheric mantle, with its convective motion that creates plumes, hotspots, and intracontinental basins. We are then linking plate tectonics with the related fields of geoscience (geodynamics), and a complete look at plate tectonics requires sub-lithospheric processes to be considered.

LEARNING OBJECTIVES

After going through this chapter, you should be able to:

- **Explain** how plate tectonics differs from and overlaps with geotectonics and mantle geodynamics.
- **Describe** how Earth's plate tectonics differs from the tectonics of the Moon and our neighboring planets.
- **Explain** how plate tectonics explains fundamental features and processes such as volcanism, sedimentary basin evolution, orogeny, and seismicity in a consistent unifying model.

1.1 Geotectonics, Plate Tectonics, and Related Terms

There are several interrelated terms that we initially need to clarify. First and foremost, there is the term tectonics. **Tectonics** comes from the Greek word tektos and relates to the structure and building of things, as in "architecture". In our case, it refers to the Earth's lithosphere, its structural characteristics, and how lithospheric structures form at various scales, from microscopic to global. Hence tectonics overlaps greatly with **structural geology**, although many of us use the term tectonics more for the large-scale structures and deformation processes of the lithosphere, often in a way that implies plate tectonic forces. However, tectonics is a general term that can relate to any type of structure-forming processes, at basically any scale. Hence, in addition to plate tectonics we have salt tectonics, thrust tectonics, glaciotectonics, and slump tectonics, which can be observed at the kilometer to outcrop scale, and microtectonics, which relates to deformational structures observed at the microscale. We also have seismotectonics, volcanotectonics, collisional tectonics, extensional tectonics, strike-slip tectonics, and gravity tectonics. The term can also be linked to the age of deformation (as in neotectonics). We could also add **tectonophysics**, which focuses on the physical aspects of tectonics. Hence the term tectonics is very general, in terms of both scale and processes.

Plate tectonics is more specific, because it is not related to one particular process such as salt movement (salt tectonics) or shortening by thrusting (thrust tectonics). Plate tectonics is a *global-scale model*. It represents a specific *lithospheric plate model*, a type of model that contrasts with the stagnant lid of other planets and collectively explains features such as lithospheric deformation, volcanism, seismicity, basin formation, orogeny, and biodiversity in space and time. We also note that many of these features are only indirectly related to tectonics in a classical sense.

> Plate tectonics is a global-scale model that explains the structure and main phenomena associated with the Earth's outer stiff layer (the lithosphere) as a consequence of the interaction of a dozen rigid lithospheric plates that move relative to each other and to the underlying mantle.

The model is primarily **kinematic** as it considers the lithosphere as a dozen large, and several smaller, stiff plates that move relative to each other and therefore collide, diverge, and slide alongside each other, creating a plate boundary mesh along which deformation, volcanic activity, and seismicity are concentrated. This model is best developed and most easily tested by considering the last 200 million years or so; it is largely based on the information from oceanic crust. There are diverging views as to when plate tectonics started and how it may have changed character through time.

While plate tectonics and other specific types of tectonics focus on the stiff outer lithospheric part of the Earth, and the crust in particular, **geodynamics** focuses on the large-scale dynamics of the entire Earth. It explores and seeks to explain the entire global system from the surface to the inner core, applying any relevant methodology and data types within geophysics and geology. Mantle convection and its relation to plate motion is an important part of geodynamics and is related to magmatism and earthquakes in the crust and intracontinental orogeny, as well as topographic effects (basins and plateaus or domes) at the surface.

Geotectonics is more general than plate tectonics, as it is not by definition linked to a predefined model. It deals with all solid Earth phenomena on a global scale, covering the entire timescale of Earth's history. Examples of large-scale geotectonic phenomena and processes that are not directly related to the plate tectonic model are salt tectonics, hotspots, mantle plumes, intracratonic basins, and the creation of dynamic topography (uplift caused by mantle convection). Geotectonics also involves smaller-scale features, but usually in the context of large-scale structures and processes. Hence, as the word implies, it is basically large-scale tectonics with the specification that it applies to the whole of planet Earth. Plate tectonics, in its original sense at least, is more concerned with the stiff lithosphere.

> Geotectonics is the part of geoscience that deals with Earth structures at all spatial and temporal scales, from surface to core, and the processes and mechanisms by which these structures form.

Geodynamics deals with the large-scale dynamics of the entire Earth, which is basically driven by gravity and fueled by variations in density and heat. It explores and seeks to explain the entire global system, involving any relevant methodology and data type within geophysics and geology, typically with a strong emphasis on physics. Mantle convection and its relation to plate motions is an important part of geodynamics, specifically referred to as **mantle dynamics**. This subject has implications for magmatism and earthquakes in the crust and intracontinental orogeny, as well as topographic effects (basins and plateaus or domes) at the surface. Geodynamics is also dealt with in this book, but because of our focus on tectonics and associated processes in the lithosphere, we have chosen to use the term plate tectonics in the title. In practice, all these terms are related and blend into each other.

1.2 Plate Tectonics: A Unifying Theory for the Earth Sciences

The Earth's atmosphere, oceans, and temperature create an environment that generates widespread river systems and glaciers, which, together with chemical weathering, continuously works to dampens and ultimately remove topography over geologic time. Hence the landscape on our continents should be flat and near sea level, which indeed it is, in most continental shields and cratons; these have not been subject to tectonic processes for the past billion years or more. When we consider the distribution of surface elevation on Earth, we see two peaks, one dominated by abyssal plains at around 4000–5000 m depth and the other on continents close to sea level (Figure 1.1). The peak near sea level relates to the erosional forces that act on rocks, while the abyssal plains relate to the isostatic equilibrium between the denser oceanic lithosphere and the underlying soft asthenosphere. The difference between oceanic and continental crust is fundamental in many ways, and having denser oceanic lithosphere with the ability to sink into the mantle is a prerequisite for plate tectonics.

Slow geological processes are important, but it is the extreme features of our planet that represent the signature of plate tectonics. Topographically, the extremities or anomalies are first and foremost our high mountain ranges and deep oceanic trenches. These positive and negative, often curvilinear, topographic features and their distribution and relations are expressions of active tectonic processes. Most fundamental surface features and associated tectonic processes fit conveniently into the plate tectonic model, where relatively rigid plates of the outer lithospheric shell move at different speeds and directions. The deepest submarine trenches are found where oceanic lithosphere sinks down under an adjacent plate margin by subduction. Volcanoes line up above the subducting plate owing to partial melting of mantle rocks above the subduction interface, forming volcanic island arcs if the upper plate is oceanic or magmatic arcs if it iscontinental. The whole ring of fire around the Pacific Ocean is dominated by such processes. Earthquakes rattle the ground most violently along subduction zones. The highest mountains and the deepest crustal roots are found where continents collide, for example in the Himalaya–Tibetan region. Submarine mid-ocean ridges together with extensive basaltic volcanism are found where plates diverge.

Then there is the atmosphere and climate. Tectonics is not directly responsible for water and oxygen, the important prerequisites for life, but it provides mountains with their different climatic zones and physical and climatic divides that enhance flora and fauna diversity. Volcanoes provide CO_2 to the atmosphere, which influences the global temperature and prevents the Earth from

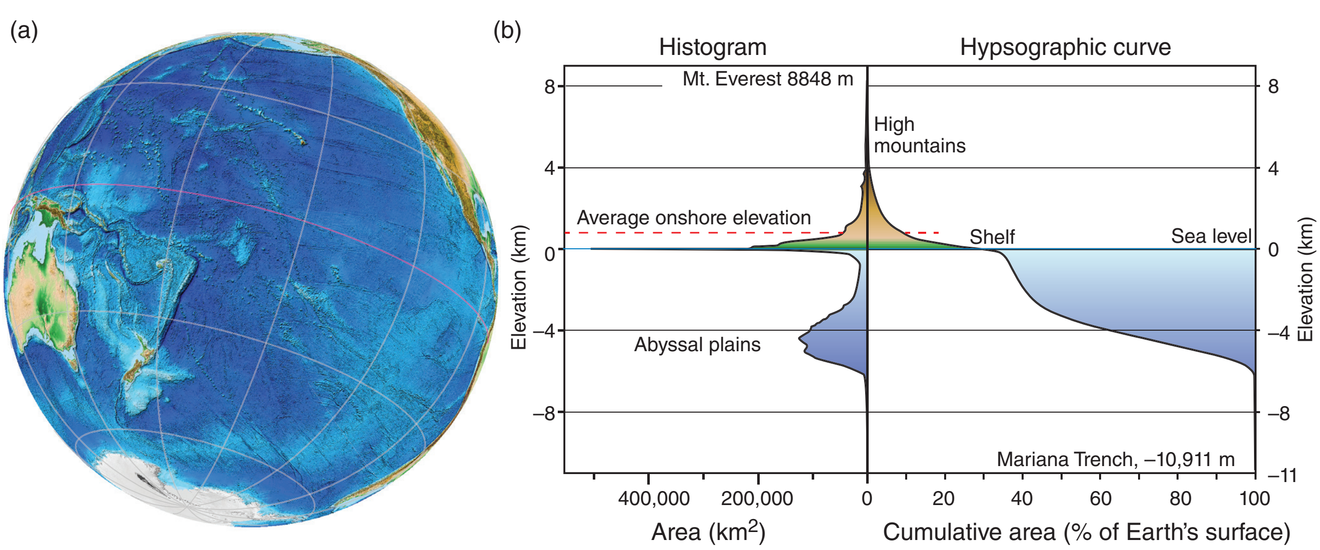

Figure 1.1 (a) View of the Pacific side of the Earth illustrates well that close to 70% of its surface is covered by oceans. The oceans cover mostly oceanic crust. Except for the special case of Iceland, very little oceanic crust is above sea level. (b) Distribution of elevation shown in the form of a histogram and a cumulative (hypsographic) curve. The bimodal distribution, with large areas of the Earth's surface just below 4000 m depth or near sea level is clear from both graphs. Modified from NOAA.gov.

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freezing over (although the snowball Earth theory claims that the Earth actually did freeze over at the end of the Precambrian), and have probably contributed to several mass extinctions, each of which fundamentally changed the evolutionary path of life.

The Different Faces of Our Planets

As indicated above, plate tectonics has made a profound imprint on the surface expression of our planet. If we compare the topographic expression of the Earth to that of the Moon and the other planets in our solar system, we find that planet Earth is fairly unique. First, the surface features on our neighboring planets are better preserved because of the lack of running water and glaciers. Second, there are considerably more circular features, many of which obviously relate to meteor impacts. The surface of the **Moon**, for example, is completely dominated by craters, most of them formed 4 to 3 billion years ago by meteor impacts and preserved because of the lack of water, atmosphere, and tectonic processes. Hence the face of the Moon owes its appearance to impact tectonics, not plate tectonics. The largest impacts caused volcanism and huge volcanic fields; the largest basaltic field can be seen by eye as large dark regions. There is also evidence of Cenozoic volcanic eruption along fissures that tell us that the interior of the Moon is still hot, probably owing to radioactive decay. However, there is no trace of past or current plate tectonic processes. The Moon is probably too small for a global plate tectonic framework with convection-based mantle dynamics to have been set up.

Mars also has a very large number of craters from impacts, particularly on its southern half. It does have some atmosphere, weather, and even small ice caps, but although there is abundant evidence of fluvial erosion and deposition, such as river channel systems and deltas, water was probably never present in the amount and with the erosional dynamics that we know from our own planet. At present there does not seem to be much water activity at all. Hence, any topographic feature created on Mars is relatively well preserved.

Mars not only has the highest mountain of the planets in our solar system (the circular Mount Olympus, a 22-km-high shield volcano). It also has a 7-km-deep canyon system, Valle Marineris, that shows up as a big scar on images (Figure 1.2). It has been suggested that this scar represents a major strike-slip or extensional fault system. If so, it would be a sign of large-scale tectonic processes (e.g., rifting). Another feature is the much lower surface elevation, and hence thinner or denser crust, in the northern part of the planet. This part also shows fewer impact structures than the southern red part, as the surface there is covered by lava flows. In addition, an outstanding volcanic province (the Tharsis rise) near the equator is a prominent feature. Together with so-called wrinkle ridges that suggest horizontal shortening, and some poorly understood linear magnetic anomalies, it seems likely that some kind of tectonic process has shaped the surface of Mars. The existence of magnetic anomalies suggests that, like Earth, Mars had a molten convective metal core in the past. Today there is no magnetic field produced by Mars, and therefore its core may have crystallized to the point that the dynamo effect no longer exists. The surface is made of more regular rocks, and density measurements show that a mantle must exist under the cool crust. However, satellite measurements indicate that the crust behaves like a single lid, shell, or plate, without any differential movements and displacement discontinuities resembling those that define plate boundaries on Earth. Hence, there is no plate tectonics on Mars, although some wonder if plate tectonic processes may have occurred on the young Mars. Martian tectonics is debated, but it would certainly be different from Earth's tectonics.

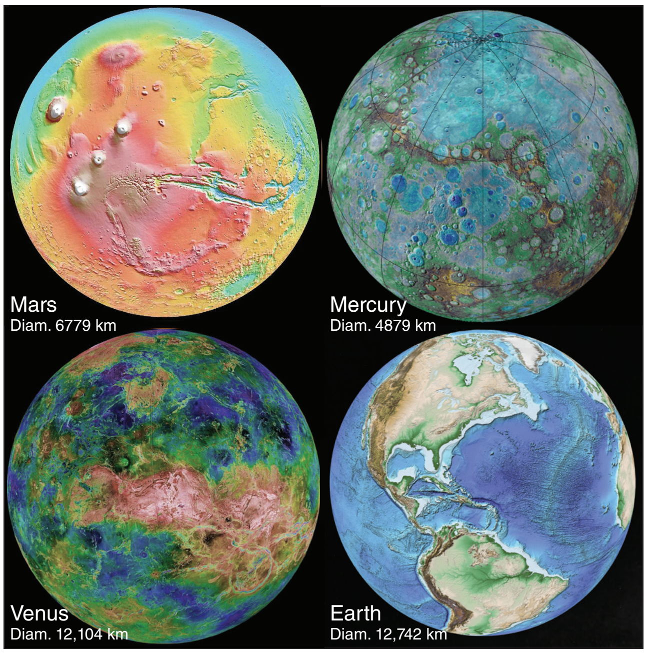

Figure 1.2 Four planets in our solar system, with different surface expressions that reflect different tectonic activities. Only Earth has plate tectonics; Mars possibly had something similar in the past and Venus is dominated by volcanic eruptions, while Mercury deforms by cooling-related contraction (single-plate tectonics). Images from NASA (Mars, Mercury, and Venus) and the ETOPO NOAA model (Earth).

Venus, which is comparable with Earth in terms of nearness and size, has a surface with relatively few craters. Its very thick atmosphere has protected it from smaller meteorites, but larger craters are also remarkably few compared with Mars, Mercury, and the Moon. This means that somehow the surface has been maintained or renewed. Winds seem to have limited effects on the surface. Volcanism is more important, where the flow of lava, either repeatedly or during a single catastrophic event, has masked former impact structures. The enormous amounts of volcanic rocks on this planet are thought to come from plumes in Venus' mantle. They may be related to convective mantle flow, but not to plate tectonics. This is supported by the almost random distribution of volcanic features, whereas on Earth most of the volcanic activity occurs along curvilinear belts related to plate boundaries. However, we do see features on Venus that can be interpreted as tectonic folds and faults. The faults appear to be extensional, related to sinking of the crust, which means that rifting has occurred and perhaps even some sort of subduction-like process if it could be demonstrated that the planet crust or lithosphere sank deeply into the interior. Why Venus, with its many similarities to the Earth, did not develop plate tectonics is not clear. Perhaps its strong volcanic layer "glued" the surface together, preventing it from developing into separate plates?

Mercury, our last example, is another planet with a surface that is well decorated with circular impact structures, and is still thought to be tectonically active. It has a molten core that is gradually cooling and thereby getting denser, and this is causing the planet to shrink. The shrinkage in turn is causing contractional deformation of its outer layer, with the formation of thrusts, folds, and reverse faults. We could call this single-plate tectonic process **shrinkage tectonics**, representing a tectonic system very different from the plate tectonics we know on our own planet.

Now returning to our planet **Earth**, we realize that its pattern of conspicuous topographic features together with the distribution of volcanoes, seismic activity, sedimentary basins, rock magnetism, rock age distribution, and many other features that will be covered throughout this book, is unique and reflects plate tectonics, where relatively rigid plates move individually and where oceanic crust is forming, cooling, and subducting in a way that keeps the internal temperature of our planet down.

In our solar system, plate tectonics involving lateral plate motion, subduction, and spreading is unique to Earth, where it has a profound impact on topography, climate, and life.

"Everything" is Linked to Plate Tectonics

Plate tectonics, as a model, has been outstandingly successful because it is able to put almost all significant geologic features and processes into a single overarching model. It explains the topographic expression of our planet, from the highest peaks to the deepest ocean floors and trenches. It explains earthquakes and volcanism. It explains the distribution of rock ages of the continents and of the oceanic crust. Mountain belts and belts of metamorphic and deformed rocks are explained, together with sedimentary basin formation and global stratigraphic patterns. The distribution of fossils and the evolution of life can be explained by changes in distance between continents through the opening and closing of oceans and by the formation of mountain chains. Sedimentary basin deposits and their characteristics also match the history of such changes, which can be studied through plate tectonic reconstructions.

The formation and distribution of natural resources can be explained in the same way. The mineralization associated with igneous activity above subduction zones (arc environments) contrasts with that going on along mid-ocean ridges and magmatic continental rifts. These are all different, with characteristics that are linked to their plate tectonic genetic environment. Also, the formation and accumulation of hydrocarbons is closely related to plate tectonics. For example, the breakup-related rifting of Pangea created a global-scale rift and rifted margin

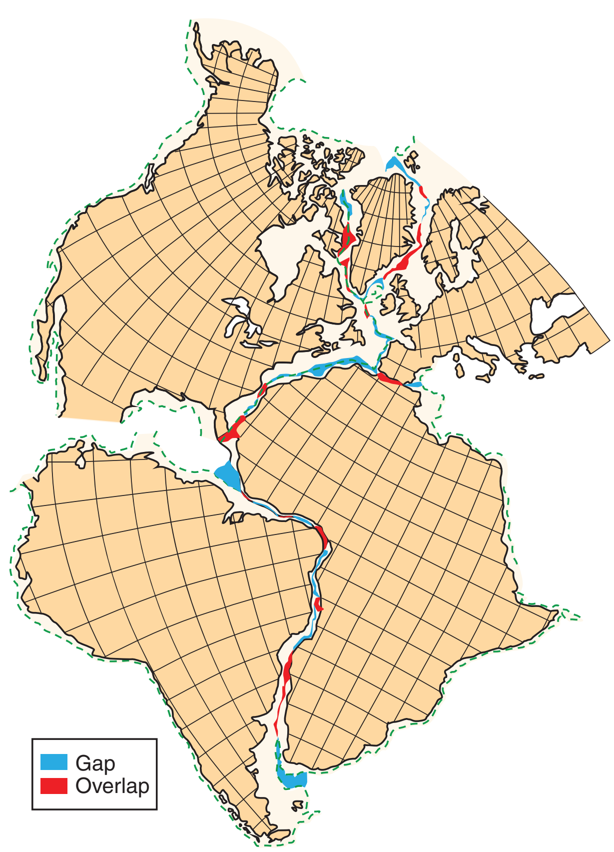

Figure 1.3 Bullard reconstruction of the Atlantic: the first computerized reconstruction of continents, published by Bullard et al. in 1965. The green dashed line is the 900 fathom depth contour, used as a proxy for the continental margin.

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environment that laid the foundation for an enormous amount of hydrocarbon resources.

Plate tectonics explains many long-standing fundamental problems in geology.

Geoscience has always had unsolved questions, and some very fundamental ones were solved with plate tectonics. A well-known example is the good fit between continental margins across the Atlantic Ocean (Figure 1.3). This had no satisfactory explanation for several hundred years, until plate tectonics and ocean-floor spreading resolved the matter. If we compare Alfred Wegner's 1924 reconstructions of the continents back to the start of the Cretaceous with modern reconstructions (Figure 1.4), we see that his model of continental drift was quite accurate. However, what was going on in the oceanic domain between the continents was not at all understood until the plate tectonics theory was formulated. Only then could the relative motion of continents be explained and put into a holistic geotectonic framework.

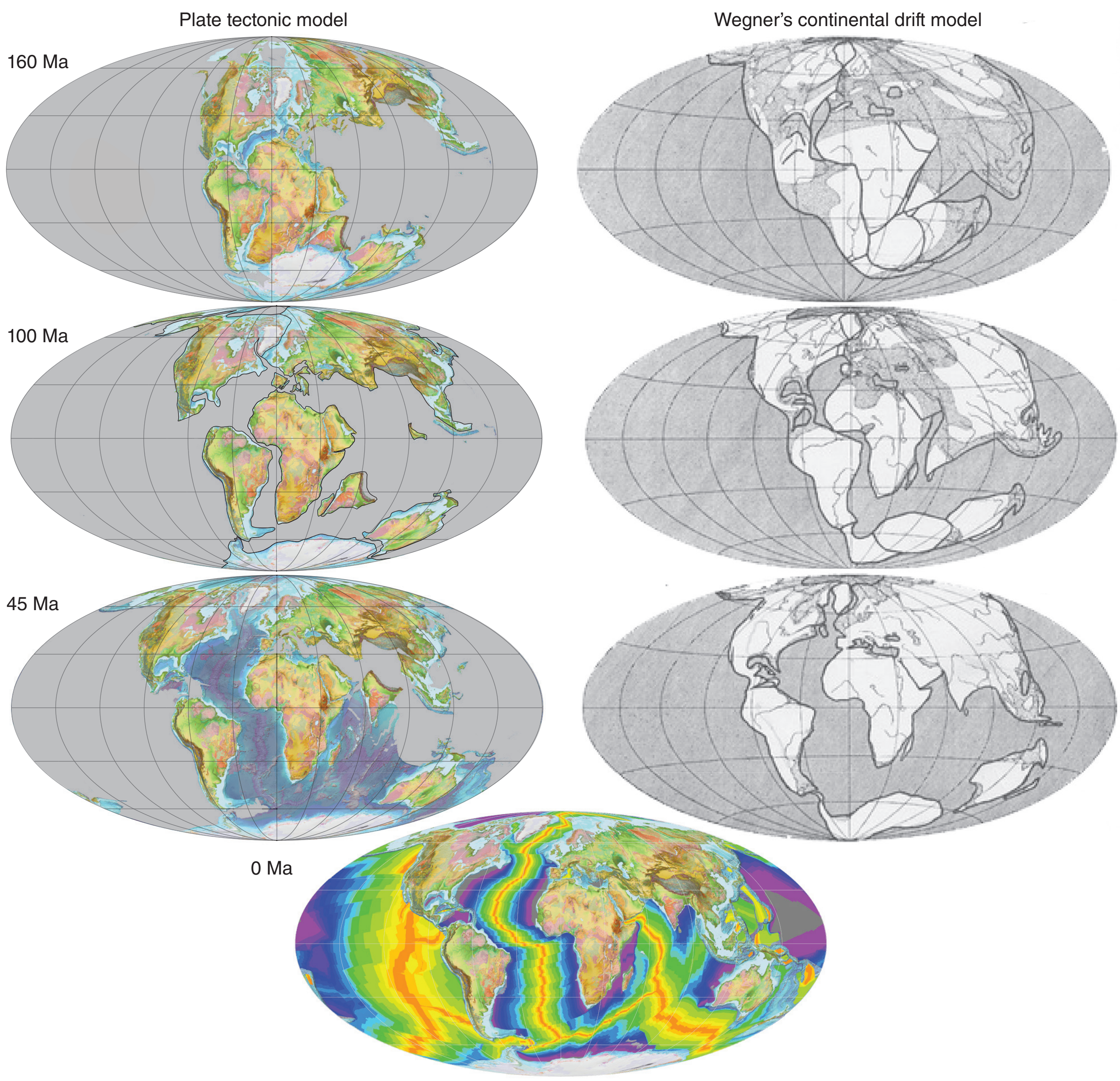

Figure 1.4 (left) Modern reconstruction of the continents at 45, 100, and 160 Ma, compared with (right) Wegner's reconstruction (Wegener, 1924). Bottom: present geography with age of oceanic crust colored from violet and dark blue (~160 Ma) to red (recent). Plate tectonic reconstructions were made by means of Gplates.

Another age-old problem solved by plate tectonics is the origin of orogenic belts and their large overthrusts. Several workers in the late 1800s concluded that kilometer-thick thrust nappes must have moved laterally several hundred kilometers, away from orogenic centers. Similar evidence emerged at the same time from the Scandinavian and Scottish Caledonides and from the Alps, and the discussion went on far into the twentieth century. The problem was that large lateral movements did not fit the geosynclinal model, which was built around vertical movements and only relatively minor horizontal shortening. In fact, the formation of orogens in general was a problem. De Sitter's textbook from 1956 has the following honest cry for help:

> *In all my descriptions of deformations of the Earth's crust I have avoided mention of the origin of the forces that caused these [orogenic] deformations, because we are still completely in the dark about these causes.*

A decade later such lateral orogenic movements made perfect sense in the context of plate tectonics, which does indeed involve large lateral relative movements of plates and their continents. The concept of collisional tectonics was then established, where continental margins collide along convergent plate boundaries, causing the formation and lateral motions of huge thrust nappes (Box 1.1).

BOX 1.1 TECTONIC FEATURES NOT DIRECTLY EXPLAINED BY PLATE TECTONICS

Plate tectonics, where differently moving plates create subduction, ocean spreading, and strike-slip motion, cannot explain every tectonic feature observed on or near the surface of the crust. Several of these are indirectly related to plate tectonics, while a few are completely separate. Here are the most important of these.

Trails of several thousand-meter-high submerged volcanic islands, with active volcanoes such as Kilauea and Maunaloa in Hawaii at their end, mark locations of **hotspots**. They form where mantle material rises in columnar channels or plumes that generate melts where they reach the base of the bottom of the lithospheric plates. Large magmatic provinces such as Iceland also form at hotspot locations. These hotspots are not directly explained by the plate tectonic model *per se*, but are "side effects" of the mantle convection processes that are working in concert with plate tectonics.

Then there are some **deep intracontinental basins** away from plate boundaries that are hard to explain. Examples are the Paraná Basin in South America and the Barents Sea basin between northern Norway and Russia. These are often called intracratonic sag basins, and several are built on former rift basins. However, the basins are not fault bounded and cannot be explained by extensional tectonics. It has been suggested that they have formed by the downwelling of mantle material, like a negative plume. If so, we have a link to mantle dynamics again, which in turn is linked to plate tectonics.

Figure B1.1.1 The 49,000-year-old Berringer Meteor Crater, Arizona, the first impact crater to be identified (1920). Photograph: NASA.

The term **intracontinental orogens** (Chapter 13) refers to orogeny going on within continents, away from plate boundaries. Hence it does not involve continent collision or subduction, but most workers now agree that intracontinental orogeny, for instance north of the Himalaya–Tibet orogen, relates to stresses generated at plate boundaries transmitted into the continents through the lithosphere, reactivating rifts or other weak structures. Hence it seems that these orogens are indirectly related to plate tectonics, even though the basic plate tectonic model predicts orogeny to occur along plate boundaries.

Impact craters (see Figure B1.1.1) are the prime example of large-scale structures that are

BOX 1.1 (CONT.)

completely unrelated to plate tectonics. Modern impact craters are very rare, and less than 200 impact craters are confirmed in total. The large ones are all old, such as the enormous 65 Ma Chicxulub crater in Mexico, the 1850 Ma Sudbury crater in Canada and the 2023 Ma Vredefort crater in Southern Africa. They were perhaps more frequent in the deep past, but plate tectonics and surface processes have hidden or destroyed them. As a curiosity, we mention that a vague link to plate tectonics has been made through the idea that huge impacts in early parts of the Earth's history may have helped trigger plate tectonic processes.

Summary

Plate tectonics is a global-scale model that explains the structure and main phenomena associated with the Earth's outer stiff layer (the lithosphere) as due to the interaction of a dozen rigid lithospheric plates that move relative to each other and to the underlying mantle. It has been outstandingly successful as a model because it explains many long-standing problems in geology and places all significant geologic features and processes into a single overarching model. Plate tectonics can help explain:

- the topographic expression of our planet;
- the position and types of earthquakes and volcanism;
- the arrangement and ages of the continents and oceanic crust;
- the disposition of mountain belts, metamorphic rocks, and sedimentary basins;
- the location of mineral and petroleum resources;
- the distribution of fossils and the evolution of life.

Within our solar system, plate tectonics involving lateral plate motion, subduction, and spreading is unique to Earth, where it has a profound impact on the topography, climate, and life. However, plate tectonics cannot explain every tectonic feature observed on or near the surface of the crust. Several of these, such as hotspots, **deep intracontinental basins, and intracontinental orogens**, are indirectly related to plate tectonics but some, such as impact craters, are completely unconnected.

Review Questions

(1) What is the key difference between the theories of continental drift and plate tectonics?
(2) Why is plate tectonics such an effective and successful theory?
(3) How does plate tectonics connect the geology and geomorphology we see at the surface of the Earth with the inner workings of our planet?
(4) What tectonic features is the theory of plate tectonics not able to explain? Give reasons.
(5) Summarize the differences between the tectonic features seen on Earth and those on the Moon, Mars, Venus, and Mercury. Why might different styles of tectonics have evolved on these bodies?

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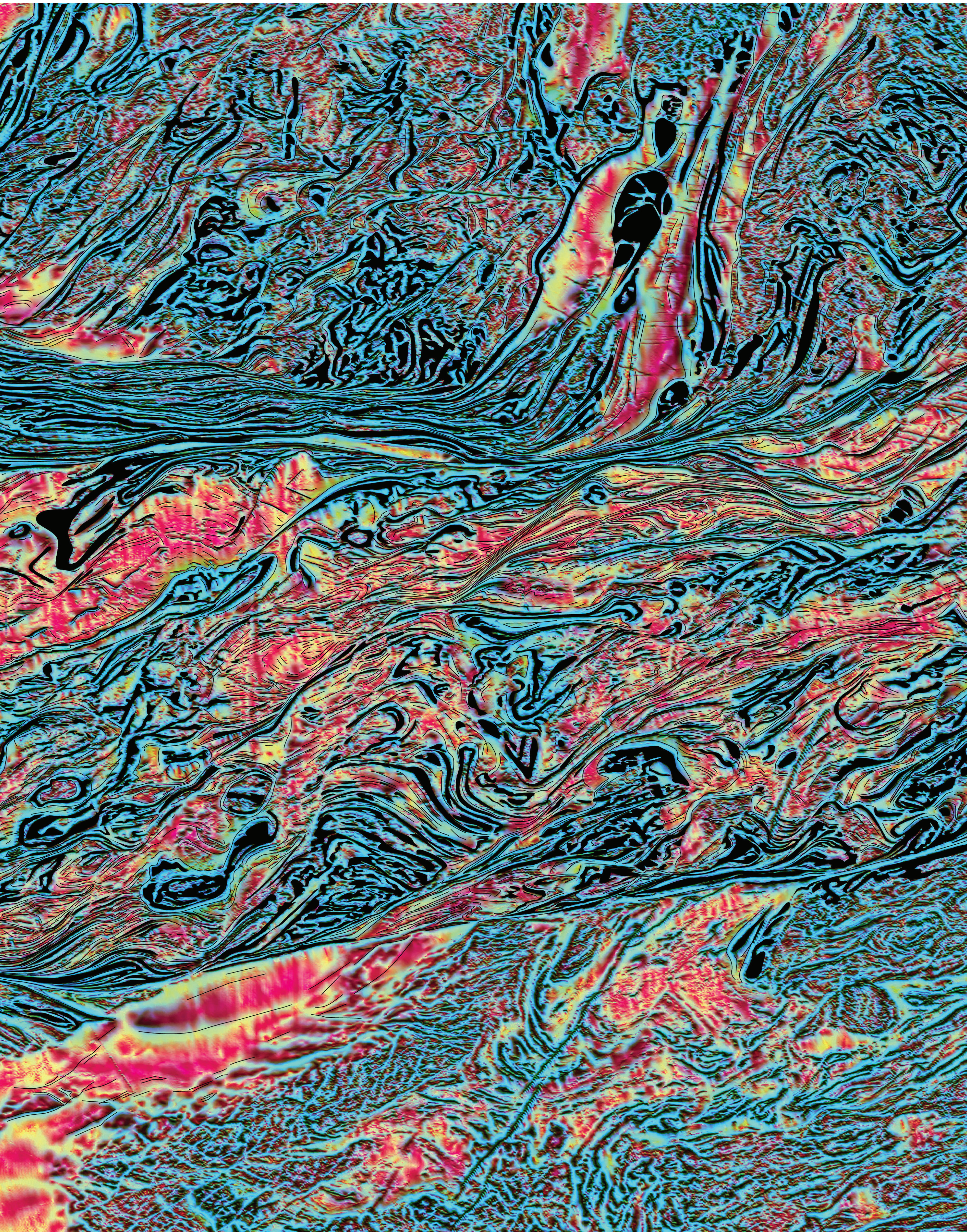

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Deformation, Stress, and Strain

Tectonic plates deform primarily along plate boundaries. Different parts of a plate deform in different ways, depending on the internal composition and structure of the plate and external factors such as temperature, depth, tectonic stress, and strain rate. Faults form in the upper crust, while shear zones develop deeper down. Layers fold, and minerals fracture or recrystallize. Deformation occurs from the grain scale to the plate scale through processes such as recrystallization, metamorphism, faulting, and shearing. At a large scale, a plate's behavior is largely captured by its rheology or vertical strength profile, which again is linked to its mineralogical composition and thermal conditions. Hence, in order to deal with plate tectonics and plate deformation, we need to have a basic understanding of these features. This chapter reviews some essential concepts of deformation, stress, and strain, from the grain scale to the scale of tectonic plates and from the surface to the base of a plate.

LEARNING OBJECTIVES

After going through this chapter, you should be able to:

- **Explain** the difference between stress and strain.
- **Outline** the way in which particles flow in a deforming rock, for different deformation types.
- **Describe** the different ways rocks can deform and how this relates to pressure and temperature.
- **Relate** structures to deformation regimes and conditions.
- **Explain** what crustal strength means and outline and explain different types of strength profiles.