INTERLUDE C

The Rock Cycle

Beds of red sedimentary sandstone and siltstone, Red Rocks, Colorado.

Molten lava extruding from a volcano in Hawaii, in the process of freezing to form igneous rock.

Contorted layering in metamorphic rock, Italy.

These photos show three major rock groups of the Earth System. Over time, the atoms in one rock type may be incorporated in another, and then another. This transfer is called the rock cycle.

C.1 Introduction

"Stable as a rock." This familiar expression implies that a rock is permanent, unchanging over time. But it isn't. In the time frame of Earth history, a span of over 4.57 billion years, atoms making up one rock type may be rearranged or moved elsewhere, eventually becoming part of another rock type. Later, the atoms may move again to form a third rock type, and so on. Geologists refer to the progressive transformation of Earth materials from one rock type to another as the **rock cycle** (**Fig. C.1**), one of many examples of cycles acting in or on the Earth. A discussion of the rock cycle illustrates the relationships among the rock types described in the previous three chapters.

By following the arrows in Figure C.1, you can see many paths around or through the rock cycle. For example, igneous rock may weather and erode to produce sediment, which lithifies to form sedimentary rock. The new sedimentary rock may become buried so deeply that it transforms into metamorphic rock, which then could partially melt and produce magma. This magma later solidifies to form new igneous rock. We can symbolize this path as

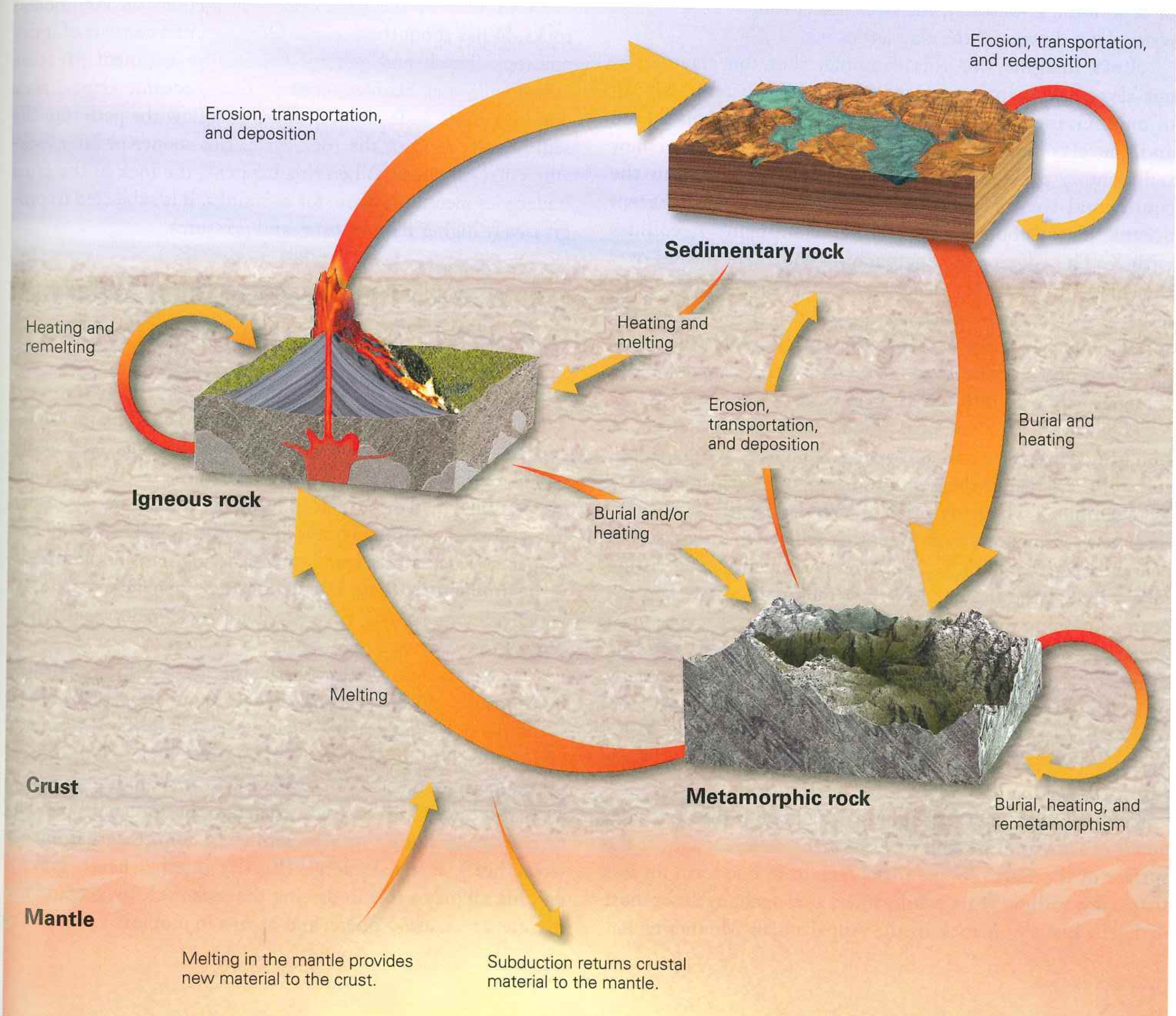
igneous → sedimentary → metamorphic → igneous.

But alternatively, the metamorphic rock could be uplifted and eroded to form new sediment which is later buried and lithified to form new sedimentary rock, without melting. This path takes a shortcut through the cycle that we can symbolize as

igneous → sedimentary → metamorphic → sedimentary.

Likewise, the igneous rock could be metamorphosed directly, without first turning to sediment. This metamorphic rock

FIGURE C.1 The stages of the rock cycle, showing various alternative pathways.



could then be eroded to produce sediment that eventually becomes sedimentary rock, defining another shortcut path:

igneous → metamorphic → sedimentary.

To get a clearer sense of how the rock cycle works, let's look at one example in the context of plate tectonics.

C.2 A Case Study of the Rock Cycle

Material can enter the rock cycle when magma rises from the mantle. Suppose the magma erupts and forms basalt (an igneous rock) at a continental hot-spot volcano (**Fig. C.2a**). Interaction with wind, rain, and vegetation gradually weathers the basalt, physically breaking it into smaller fragments and chemically transforming it to yield clay. Water washes the newly formed clay away and transports it downstream—if you've ever seen a brown-colored river, you've seen clay traveling to a site of deposition. Eventually, the river reaches the sea, where the water slows down and the clay settles out.

Let's imagine, for this example, that the clay settles out along the margin of Continent X and forms a deposit of mud. Gradually, through time, the mud becomes buried and the clay flakes pack tightly together to form a new sedimentary rock, shale. The shale resides 6 km below the continental shelf for millions of years, until the adjacent oceanic plate subducts and another Continent, Y, collides with X. The edge of the encroaching continent pushes over the shale, buries it very deeply, and shears it. As the mountains grow, the shale that had once been 6 km below the surface ends up 20 km below the surface, and under the pressure and temperature conditions present at this depth, it metamorphoses into schist (**Fig. C.2b**).

The story's not over. Once mountain building stops, erosion grinds away the mountain range, and exhumation brings some of the schist to the ground surface. This schist erodes to form sediment, which is carried off and deposited elsewhere to form new sedimentary rock. But other schist remains preserved below the surface (**Fig. C.2c**). Eventually, continental rifting takes place at the site of the former mountain range, and the crust containing the schist begins to split apart. Rifting causes decompression melting in the mantle. The rising melts bring so much heat into the crust that some of the schist partially melts and a new felsic magma forms. This felsic magma rises to the surface of the crust and freezes into rhyolite, a new igneous rock (**Fig. C.2d**). In terms of the rock cycle, we've gone full circle, having once again made igneous rock.

Not all atoms pass through the rock cycle at the same rate, and for that reason we find rocks of many different ages at the surface of the Earth. Some rocks remain in one form for less than a few million years, while others stay unchanged for most of Earth history. A rock in the Appalachian Mountains has passed through stages of the rock cycle many times during the past few hundred million years, because the eastern margin of North America has been subjected to multiple events of basin formation, mountain building, and rifting during the last billion years. In contrast, some 3 billion-year-old mafic and ultramafic rocks found in the interiors of continents have not yet passed the first stage of the rock cycle. Studies show, however, that such long-lived rocks account for a very small proportion of the crust—most crust has been through at least a couple of stages in the rock cycle.

Most atoms that comprise continental rocks never return to the mantle, because continental crust is buoyant and does not subduct. However, a small amount of sediment that erodes off a continent ends up in deep-ocean trenches, and some of this gets carried back into the mantle by subduction. And recent research suggests that metamorphic and igneous rocks at the base of the continental crust may be scraped off and transported down into the mantle by subduction.

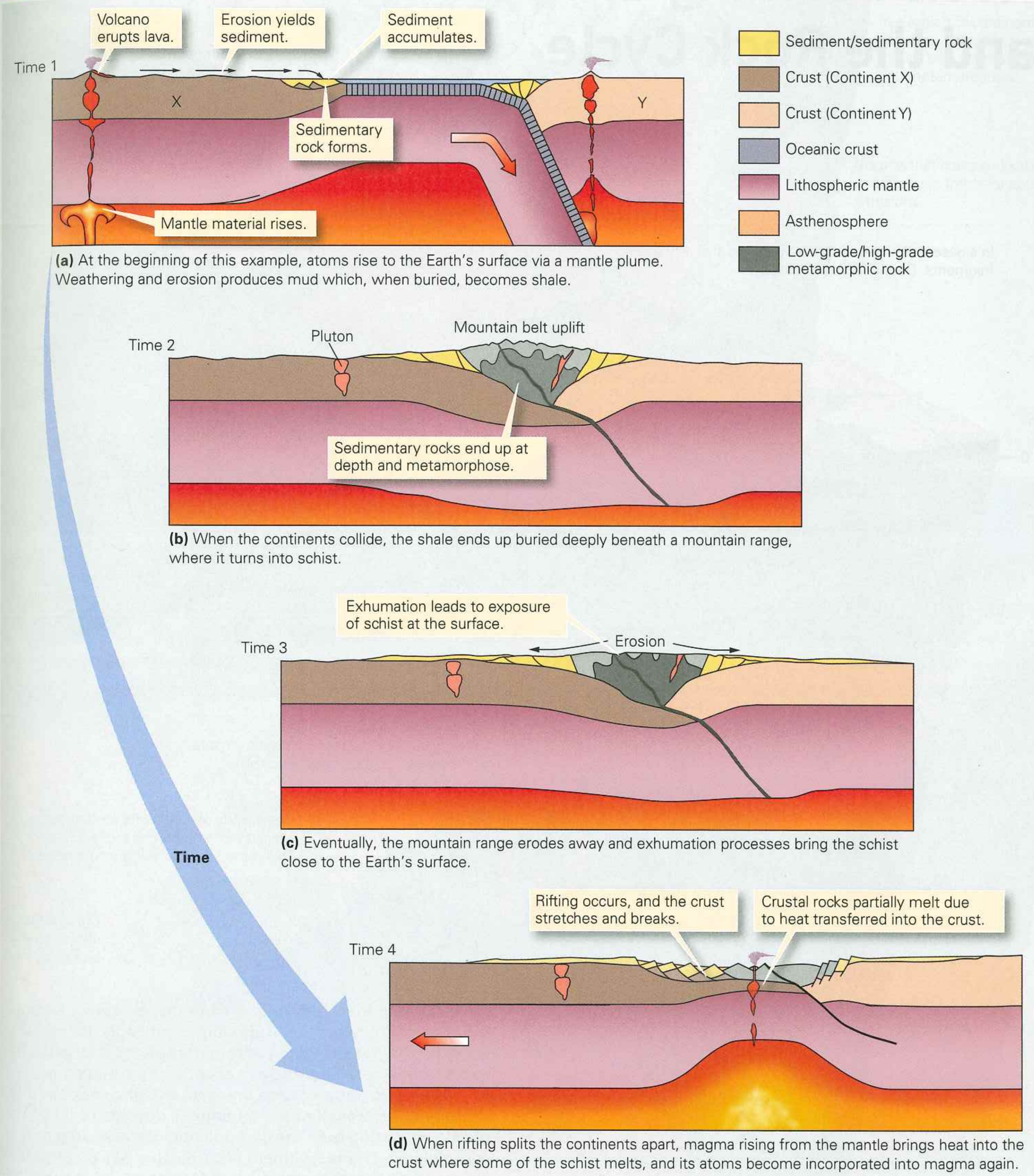
Our tour of the rock cycle has focused on continental rocks. What about the oceans? Oceanic crust consists of igneous rock (basalt and gabbro) overlain by sediment. Because a layer of water blankets oceanic crust, oceanic crustal rock does not erode and generally does not follow the path into the sedimentary loop of the rock cycle. But sooner or later, oceanic crust subducts. When this happens, the rock of the crust undergoes metamorphism, for as it sinks, it is subjected to progressively higher temperatures and pressures.

C.3 What Drives the Rock Cycle in the Earth System?

The rock cycle occurs because the Earth is a dynamic planet and there are many rock-forming environments (see **Geology at a Glance**, pp. 214–215). The planet's internal heat and gravitational field drive plate movements and plume-associated hot spots. Plate interactions cause the uplift of mountain ranges, a process that leads to weathering, erosion, and sediment production. Plate interactions also generate settings in which metamorphism occurs, where rock melts, and where sedimentary basins develop.

At the surface of the Earth, the gases initially released by volcanism collect to form the ocean and atmosphere. Heat (from the Sun) and gravity drive convection in the atmosphere and oceans, leading to wind, rain, ice, and currents—the agents of weathering and erosion. In the Earth System, life also plays a key role by adding corrosive oxygen to the atmosphere and by directly contributing to weathering. In sum, external energy (solar heat), internal energy (Earth's internal heat), gravity, and life all play a role in driving the rock cycle by keeping the mantle, crust, atmosphere, and oceans in motion.

FIGURE C.2 An example of the rock cycle in the context of plate tectonics.



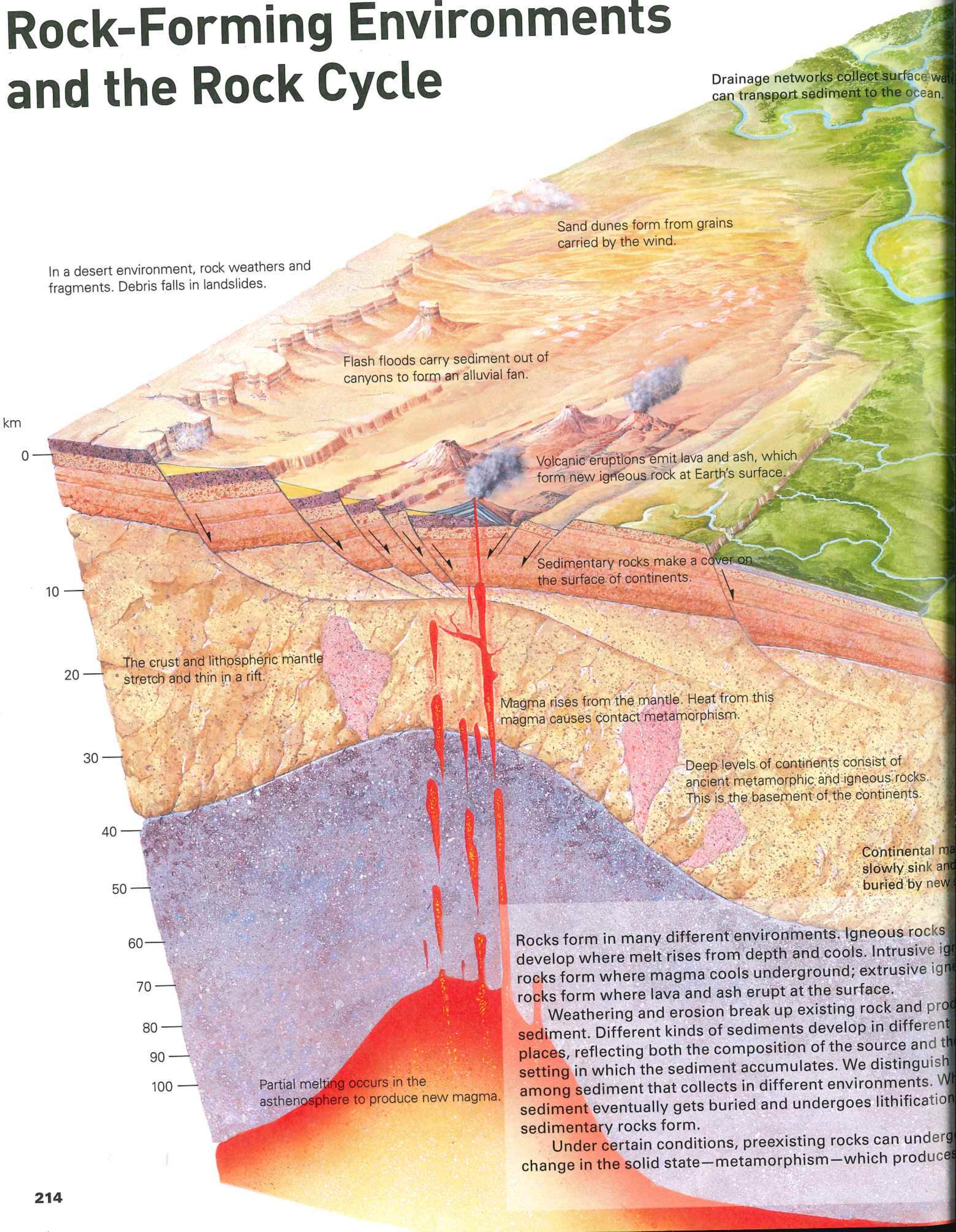
(a) At the beginning of this example, atoms rise to the Earth's surface via a mantle plume. Weathering and erosion produces mud which, when buried, becomes shale.

(b) When the continents collide, the shale ends up buried deeply beneath a mountain range, where it turns into schist.

(c) Eventually, the mountain range erodes away and exhumation processes bring the schist close to the Earth's surface.

(d) When rifting splits the continents apart, magma rising from the mantle brings heat into the crust where some of the schist melts, and its atoms become incorporated into magma again.

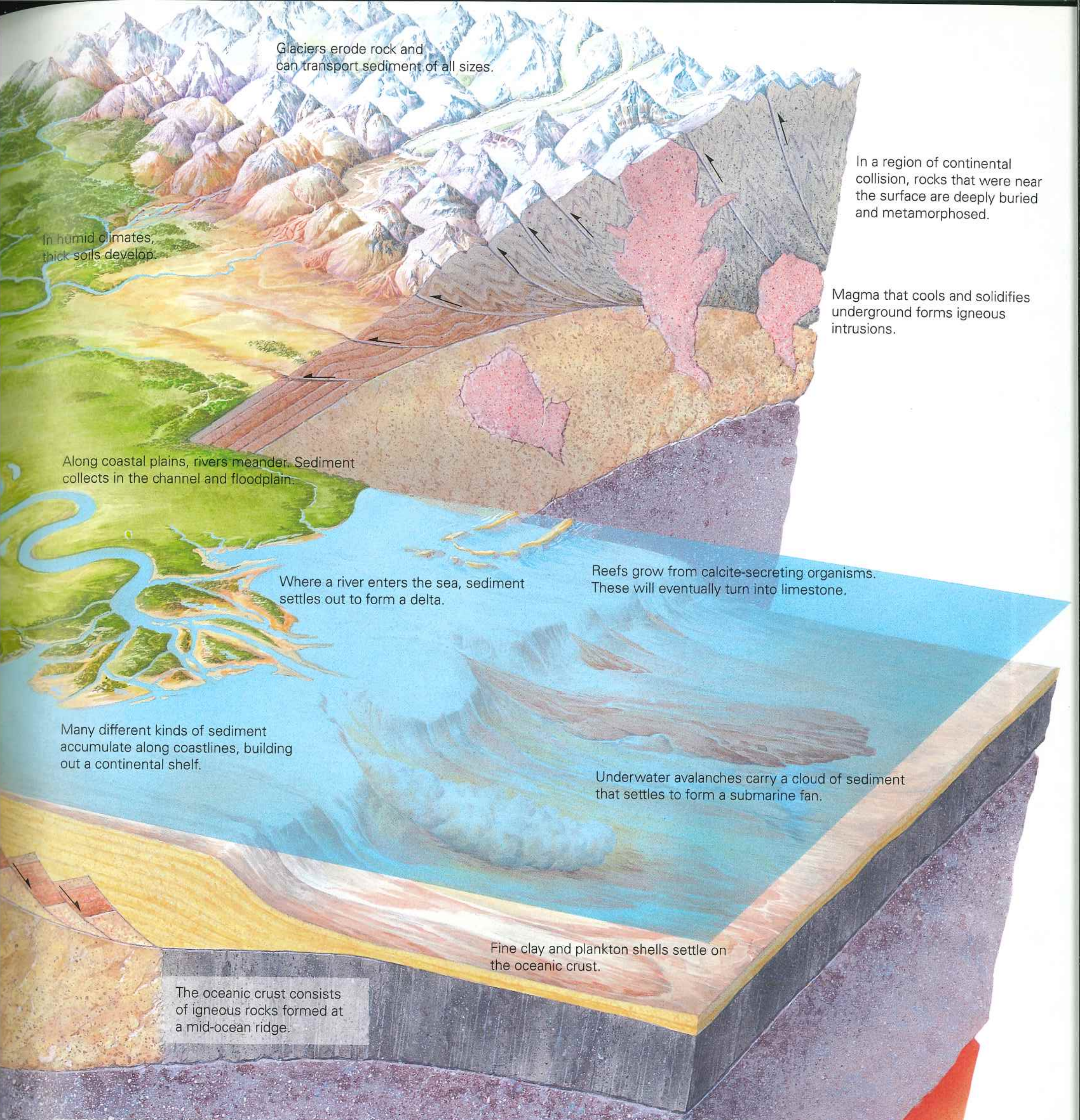
Rock-Forming Environments and the Rock Cycle



Rocks form in many different environments. Igneous rocks develop where melt rises from depth and cools. Intrusive ig rocks form where magma cools underground; extrusive ign rocks form where lava and ash erupt at the surface.

Weathering and erosion break up existing rock and pro sediment. Different kinds of sediments develop in different places, reflecting both the composition of the source and th setting in which the sediment accumulates. We distinguish among sediment that collects in different environments. W sediment eventually gets buried and undergoes lithification sedimentary rocks form.

Under certain conditions, preexisting rocks can underg change in the solid state—metamorphism—which produces



metamorphic rocks. Contact metamorphism is due to heat released by an intrusion of magma. Regional metamorphism occurs where tectonic processes cause rocks from the surface to be buried very deeply.

Because the Earth is dynamic, environments change through time. Tectonic processes cause new igneous rocks to form. When exposed at the surface, these rocks weather to make sediment. The slow sinking of some regions creates sedimentary basins in which sediment accumulates and new sedimentary rocks form. Later, these rocks may be buried deeply and metamorphosed. Uplift as a result of mountain building exposes the rocks to the surface, where they may once again be transformed into sediment. This progressive transformation is called the rock cycle.