Earth: Portrait of a Planet

— Errata, Addenda, and Clarifications —

In spite of our best efforts, a few errors (*errata*) crept into the first edition of *Earth: Portrait of a Planet.* Also, some readers have suggested *addenda* to clarify or expand on points in the text, or have suggested places where the statements in the text need clarification. (In some cases, these *addenda* cover material that was cut from the final version of the text to save space.) Fortunately, with Web technology, we can correct *errata* as they come to our attention and provide *addenda* and clarifications where appropriate. We are very grateful to readers who have sent suggestions.

Please check the "Errata, Addenda, and Clarifications" Web page for each chapter before you read through the chapter, and mark the correction on the text to avoid confusion. We apologize for the errors, most of which will be corrected in the second printing of the first edition, but some of which will linger until the second edition appears. Thank you for your patience.

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CHAPTER 1: COSMOLOGY AND THE BIRTH OF EARTH

<u>p. 23, ‘‘The Doppler Effect’’ (*clarification*)</u>

The text implies that the Doppler effect applies to light sources only when the light source is moving at velocities greater than about half the speed of light. In fact, the Doppler effect always applies, but it is only noticeable when the source is moving greater than about half the speed of light.

<u>p. 24, Figure 1.11 (*erratum*)</u>

In part (b), the prism looks like a tetrahedron; it should not. Prisms used to make spectrographs are wedge-shaped, with two triangular ends and three rectangular faces. In part (c), there should be two arrows (not one), each pointing to a white line. Also, note that on a real spectrogram, the absorption lines are black (not white), because they represent locations on the spectrum where no light energy appears. Also, the spectra obtain by spectrographs usually have red light on the right, and violet light on the left.

p. 25, ‘‘Aftermath of the Big Bang’’ *(erratum and clarification)*

The first paragraph says that "thermal energy (energy caused by the vibration and movement of molecules) kept even the smallest atomic pieces, quarks, from sticking together." In fact, since molecules didn't exist yet, we cannot define thermal energy in terms of their motion. ‘‘Molecules’’ should be replaced by ‘‘particles.’’

Astrophysicists think that neutrons and protons formed within the first second after the big bang, so by definition, hydrogen nuclei (consisting only of a single proton) existed by the end of the first second. Helium nuclei formed within the first three minutes, but the joining of nuclei with electrons to form neutral atoms took another 300,000 years or so. Also, to be precise trace amounts of other light-weight elements (e.g. lithium, beryllium, and boron) formed during the big bang.

The last sentence of the first paragraph defines a nebula as a cloud of gas or dust. While this statement is correct, it is a little confusing in the context of this paragraph, because "dust" in the modern universe includes heavy atoms, and heavy atoms did not form during the big bang.

p. 25, ‘‘Star Formation’’ -- Centrifugal vs. Centripetal Forces *(clarification)*

Commonly, students who have just finished a physics course will grimace when they read the first paragraph of this section and see the term "centrifugal force." They may have the impression that centrifugal force "does not exist" and that the paragraph should, instead, use the term "centripetal force." Actually, both terms can be used, but which one is appropriate in a given discussion depends on the reference frame in which the force is being described. (By **reference frame**, we mean the context or surrounding relative to which we describe what is happening to an object.) Here, we clarify the distinction between centripetal and centrifugal force.

When an object moves in a circular path around a fixed point, the object feels a force that pulls it toward the fixed point. Without this **centripetal force**, the object would leave its circular path and move in a straight line. For example, if you tie a hollow ball to the end of a piece of string and swing it around your head, the string exerts an inward-directed centripetal force on the ball. If the string breaks, the ball follows a straight-line path that is tangent to its orbit exactly at the point where it was when the string broke. Note that centripetal force exists with respect to a fixed reference frame that is outside the moving ball. For example, the centrifugal force exists with respect to your fixed body.

Let's now imagine that the ball is hollow, and contains a small pea. As the ball starts to swing around, force pushes the pea to the outer edge of the ball. This force is called **centrifugal force**. Note that the term only has meaning in the reference frame defined by the orbiting ball—there is no such thing as centrifugal force with respect to a fixed reference frame. This distinction often leads to misuse of the term and to statements like "There is no such thing as centrifugal force." Actually, there is such a thing as centrifugal force, but the term can only be used if the reference frame is moving in an orbit. To make this distinction, physicists refer to centrifugal force as a "pseudo-force" because it exists only in the reference frame of the moving object, not in an external reference frame.

p. 25, ‘‘Star Formation’’ -- Nucleosynthesis *(clarification)*

Astrophysicists use the term **nucleosynthesis** to refer to the process by which small particles or nuclei fuse to form larger nuclei.

pp. 25-28, “ Element Factories’’ *(clarification)*

The process of forming elements is more complex than could be described in the text. Astrophysicists have discovered that nuclear fusion reactions ("burning") take place in the core of a star. An atmosphere of hot gas surrounds this core. In the Sun, when burning uses up all the hydrogen in the core, helium in the core then starts to burn. Elements larger than helium cannot burn in a star the size of our Sun. But in such stars, carbon atoms form by fusing three atoms of helium together, and nitrogen and oxygen atoms form when hydrogen nuclei fuse to carbon atoms (this overall process is called the CNO cycle). Since nitrogen and oxygen form in Sun-sized stars, the book should have said that *some* elements larger than carbon can develop in Sun-sized stars, even though most such elements form in larger stars.

Larger elements form in larger stars and supernovae form when nuclear decay releases neutrons which then fuse with smaller atoms to form larger ones. When the neutrons decay and become protons, atoms with larger atomic numbers develop. By this process, very large atoms can actually form in large stars, not just supernovae. But the process of forming very large atoms happens much more rapidly in supernovae.

In a high-mass star (> ten solar masses), atoms as large as iron can undergo burning (that is, can fuse to form larger atoms). Heavier elements are made by neutron capture: neutrons fuse on to the nucleus, then decay to form protons.

The text gives the impression that elements only spray out into space as a result of stellar death (either by forming a red giant or a supernova). But, as stated elsewhere in the text, highly energetic atoms are always escaping from stars--this steady stream of atoms comprises the solar wind. Note, however, that during a red giant phase, a star loses 10 to 100 million times more mass per year than is lost by the production of the solar wind, and during a supernova explosion

p. 27, Figure: ‘‘The Birth of the Earth-Moon System” *(erratum)*

The image in the center (above the title) that shows the planetesimals surrounding the newborn Sun gives the impression that the planetesimals occur in a spiral. In fact, they occur in rings that are concentric around the Sun.

p. 29, ‘‘Forming Our Solar System’’ *(clarification and erratum)*

The definition of a "planetary nebula" given in the text is outdated. Astronomers consider a planetary nebula to be an old star with a cloud of dust and gas around it. Since planetary nebulae tend to be colored, they were thought to be planets when first discovered. In modern nomenclature, a nebula out of which a star and planets form is called a **protoplanetary disk**. The particular protoplanetary disk out of which our solar system formed can also be called the "solar nebula."

The text gives the impression that our solar system formed only out of gas, and that the gas condensed into dust within the protoplanetary disk. In fact, the protoplanetary disk also contained dust that had formed elsewhere in space.

CHAPTER 2: JOURNEY TO THE CENTER OF THE EARTH

p. 44, ‘‘Clues from Measuring the Earth's Density’’ *(erratum and addendum)*

The sequence of discovery concerning the Earth's density needs a bit of clarification. Work in the Andes, carried out in the 1740s by Pierre Bouguer, who used a pendulum to measure gravitational forces, demonstrated that the strength of gravitational pull varies with elevation. Nevil Maskelyne, the British Royal Astronomer, came up with his hypothesis for weighing the whole Earth in 1774-76, simply by thinking about Newton's laws. He came up with the equation

$$M_E = (R_E^2/R_M^2) \times (M_M/\tan\beta),$$

where M_E is the Earth's mass, R_E is the Earth's radius, R_M is the distance between the plumb bob and the mountain, M_M is the mass of the mountain, and ß is the angle of deflection between the vertical and the plumb bob. Maskelyne proposed to measure the deflection of a plumb bob to test the hypothesis by traveling to Schiehallion Mountain in Scotland. (Thus, the mountain in Figure 2.10 should be Schiehallion.) Charles Hutton used Maskelyne's data from Schiehallion and came up with a density of 4.5 gm/cm^3 (specification of the results using the metric system actually happened later, for the metric system hadn't been invented in Maskelyne's day). In 1778, English physicist and chemist Henry Cavendish, using a different method, came up with the estimate of 5.45 gm/cm^3, which is fairly close to modern estimates.

CHAPTER 3: DRIFTING CONTINENTS AND SPREADING SEAS

p. 51, Introduction *(addendum)*

Wegener was not the first to propose drift. The idea had been proposed by the mid-nineteenth century, and was suggested by an American geologist, Frank Taylor, in 1910. But Wegener's predecessors did not provide the clear, well-thought-out evidence that Wegener did, and their proposals were largely ignored.

p. 52, Introduction *(erratum)*

The Greek word *tekton* is a noun, not a verb. So it means "builder" or "carpenter,’’ not "to build."

p. 56, ‘‘Criticism of Wegener's Ideas’’ *(addendum)*

Wegener's ideas were roundly criticized at a 1926 meeting organized by the American Association of Petroleum Geologists. Though the concept of continental drift was not accepted by most North American and European geologists, some found the idea appealing, even after 1926. Many of these supporters were geologists who lived and/or worked in the southern hemisphere, for they were more familiar with the data that Wegener's model so elegantly explained. In fact, some of the evidence for drift attributed to Wegener actually was proposed by other geologists subsequent to Wegener’s book. Wegener himself continued to work on the idea, and finished the fourth edition of his book in 1929.

p. 71, ‘‘Interpretation of Marine Anomalies’’ *(erratum)*

The codiscoverer of the theory for interpreting marine magnetic anomalies was Drummond Matthews (not "Mathews").

p. 75, Suggested Reading (erratum)
The title of H.E. LeGrand's book is *Drifting Continents and Shifting Theories*.

CHAPTER 4: THE WAY THE EARTH WORKS: PLATE TECTONICS

p. 95, Figure 4.20 *(erratum)*
The Yellowstone hot-spot track was omitted. There should be a short track that extends to the west-southwest of Yellowstone.

p. 104, Suggested Reading *(erratum)*
The coauthor of the last book on the list is R.J. Twiss (not "Twis").

CHAPTER 5: PATTERNS IN NATURE: MINERALS

p. 110, Figure 5.1 *(addendum)*
The scepter shown is the British royal scepter, containing one of the Cullinan Diamonds referred to in Box 5.2 on p. 126.

CHAPTER 6: UP FROM THE INFERNO: MAGMA AND IGNEOUS ROCKS

pp. 145-46, Box 6.2 *(addendum)*
It is important to note that not all minerals listed in Bowen's reaction series appear in all igneous rocks. For example, a mafic magma will initially crystallize olivine, but the magma will have entirely frozen before quartz ever has a chance to crystallize.

p. 155, Figure 6.17 *(errata and addendum)*
Basalt and gabbro are interchanged on this figure. Basalt is a *fine-grained* mafic igneous rock, and gabbro is a *coarse-grained* mafic igneous rock. The rock names are correctly described in the text. In the right-hand column, the elements Na and Ca are interchanged. Na-plagioclase dominates in silicic rocks, while Ca-plagioclase dominates in mafic rocks. This fact is correctly shown in Figure 6.6 on page 146.

There is debate as to whether the amphibole field in the right column goes all the way to the top of the diagram, for amphibole is very rare in silicic igneous rocks.

p. 158, ‘‘The Formation of Igneous Rocks at Rifts’’ *(erratum and addendum)*
Land exposure of the Mid-Continent Rift starts at the western tip of Lake Superior, at the Wisconsin-Minnesota border. The rift then tracks south-southwest across Minnesota. Thus, the phrase "Michigan's Lake Superior" is misleading. However, a branch of the Mid-Continent Rift underlies Lake Superior, and another branch cuts south-southeast across Michigan.

CHAPTER 7: A SURFACE VENEER: SEDIMENTS AND SEDIMENTARY ROCKS

p. 167, Figure 7.6 caption *(erratum)*
The last line should read , ‘‘salt comes from sea spray," not "salt spray."

p. 187, Figure 7.24 *(erratum)*
In the stratigraphic column shown to the left of the photo, the name of the third formation down is "Coconino" (not ‘‘Cononine"). It is correctly spelled elsewhere in the book.

CHAPTER 8: CHANGE IN THE SOLID STATE: METAMORPHIC ROCKS

p. 209, Figure 8.9a *(clarification)*
In the right-hand side of the figure, showing the collapsed house of cards, the horizontal arrows correctly point inward because the horizontal stress, caused only by air pressure, is compressive. Our point is that the inward push caused be air is less than the downward push caused by the foot.

p. 218, Environments of Metamorphism painting *(modification)*
The image of the convergent margin in the upper left corner should also show a forearc basin.

p. 221, Figure 8.25 *(erratum)*
Label (a) should read "metamorphosed" (not "metamophosed"). In (b), the 20° symbol just above the black dot should be removed. Note that the scale in (b) is not the same as in (a); vertical dimensions in (b) are about 50% too long.

p. 225, Figure 8.29 *(erratum)*
The Canadian Shield is much larger than is shown on this figure. Please see Figure 13.9 (p. 402) for a more accurate depiction.

CHAPTER 9: THE WRATH OF VULCAN: VOLCANIC ERUPTIONS

p. 255, ‘‘Eruptions Along Mid-Ocean Ridges” *(clarification)*
The phrase "veritable Garden of Eden" appears to be misleading, because of biblical implications. Replace with "thriving ecosystem.’’

p. 263, ‘‘Diverting Flows’’ *(erratum and addendum)*

The town in Sicily that was threatened by lava is Catania, not "Cantania," and its inhabitants are Catanians, not "Cantanians." The eruption occurred in 1669, and the lava flow covered only part of the town—the old city walls protected the remainder. Thus, it was a seventeenth-century, not twentieth-century, eruption.

pp. 264-65, "Volcanoes and Civilization" *(addendum)*
There is still substantial debate about whether the eruption of Santorini really had an impact on the Minoan culture, for the culture survived for a while after the eruption. It is clear, however, that the eruption buried the city of Akrotiri on Santorini. It appears that the town was evacuated quickly before the eruption, because archaeologists did not find bodies or jewelry when they excavated the town. Akrotiri workmen, however, left behind buckets of plaster they were using to repair damage from an earthquake.

p. 265, ''Volcanoes on Other Planets'' *(erratum)*
The plural of mare is "*maria*,'' not "*mares*."

CHAPTER 10: A VIOLENT PULSE: EARTHQUAKES

p. 277, ''Faulting in the Crust'' *(erratum)*
The offset stream should have undergone right-lateral displacement, but instead looks as though it has undergone left-lateral displacement.

pp. 285-87, "Defining the Size of an Earthquake" *(clarification, including contributions by Tom Henley)*
Most of the time, the popular media specify the size of an earthquake with a phrase like "The earthquake measured 4.8 on the Richter scale." In fact, there are several ways of determining an earthquake's magnitude, and not all yield the same number. However, all magnitude scales in use are logarithmic—that is, they are based on powers of 10, as in the scale originally proposed by Charles Richter in 1935. This means that an increase of one unit of magnitude, say from 4 to 5 on the original Richter scale, represents a 10-fold increase in the maximum wave amplitude on a seismogram.

Recently, it was discovered that the original Richter scale badly underestimates the size of or, more precisely, the energy released by very large earthquakes. Determining the magnitude from the maximum amplitude of a particular wave or vibration on a seismogram does not work well for large earthquakes. As a result, a magnitude 8.5 earthquake does not release 10 times as much energy as a magnitude 7.5 earthquake. The discussion below is intended to clarify this situation, and to give a fuller picture of what we mean by "earthquake magnitude." Note that some scales use a small "m," while others use a capital "M."

Richter defined his original scale (also called the **local magnitude scale**, represented by the abbreviation M_L) by measuring the maximum amplitude of a vibration recorded by a short-period seismograph called a "Wood-Anderson seismograph" (after its inventors), corrected for the distance between the earthquake epicenter and the seismograph. This seismograph provides a good record of seismic body waves with a period of about 1 second. (The "period" for a set of earthquake waves is the time interval between the arrivals of successive crests of the waves on a seismogram. Stated another way: period = 1/frequency.) The M_L scale, developed in the 1930s, was calibrated based on the way shallow (less than16 km deep) earthquakes behave in southern

California, where the material making the crust is relatively weak and therefore absorbs earthquake energy (as a boxing glove absorbs the energy of a blow with your fist), and it applies only to nearby earthquakes.

To apply Richter's concept to the description of distant earthquakes, seismologists developed a scale for **surface-wave magnitude** (abbreviation M_S). This scale is based on measurements of the amplitudes of Rayleigh waves that have a frequency of about 20 seconds. It is useful for earthquakes that are far (more than 1,500 km) from the recording station, but not for deeper earthquakes (more than 50 km), because deep earthquakes do not create large surface waves. For deeper earthquakes, it's better to use m_b, or the **body-wave magnitude scale**, which is based on measurements of P-wave amplitude.

The m_b and the M_s scales cannot accurately define the size of great earthquakes, because the scales "saturate" for large earthquakes: this means that for earthquakes larger than a given size, the scale gives roughly the same magnitude regardless of how large the earthquake really is. Thus, an earthquake with an m_b or M_S of 8 could actually be much larger than a real magnitude 8 earthquake. Because of this problem, the **seismic-moment magnitude scale**, developed in 1977, is really preferable for describing very large earthquakes.

We can define the seismic moment (M_0) as $M_0 = \mu Ad$, where μ is the "shear modulus" (a measure of how much force it takes to change the shape of rock), A is the area of the portion of the fault that has slipped, and d is the average displacement on the fault. Seismologists can estimate seismic moment from the seismogram. The **seismic-moment magnitude** (M_w) is defined as

$$M_w = (2/3)\log_{10}M_0 - 10.73.$$

This definition makes M_W values compatible with m_b and M_s values for lower-magnitude earthquakes. While there are still some uncertainties in M_w for very large earthquakes, it better represents the contrast in energy released by different-size earthquakes. M_w numbers may be different from M_S numbers. As an example, the great 1964 earthquake in Alaska had an M_S of 8.4 but an M_w of 9.2, while the 1906 San Francisco earthquake had an M_s of 8.3 and an M_w of 7.9. Since M_L, m_b, and M_s can be readily determined, they are still used in appropriate circumstances.

An earthquake releases energy, somewhat like an explosion releases energy. Earthquake energy can be calculated by the equation

$$\log_{10}E = 4.8 + 1.5M.$$

In this equation, E is the energy measured in joules ($1\ J = 1\ kg \cdot m^2/s^2$), and M is the magnitude. We can use this equation to see how the size of the great Alaskan earthquake was underestimated. The energy determined by using this equation with the value for M_W is twenty-two times the energy determined by using the equation with the value for M_S. We can also compare this energy with the energy produced by explosions. The atomic bomb that exploded in Hiroshima in 1945 produced as much energy as an $M_s = 5.3$ earthquake. Note that regardless of how you specify the magnitude, a large earthquake that occurs at a shallow depth causes much more damage than a large earthquake that occurs at a great depth. This is because earthquake energy gets absorbed as it passes through the Earth—because of interference between waves, and because as the waves travel farther, the wave energy spreads out over a broader area, and because of friction.

CHAPTER 11: CRAGS, CRACKS, AND CRUMPLES: CRUSTAL DEFORMATION AND MOUNTAIN BUILDING

p. 326, Figure 11.11 *(errata)*
In order for the strike symbol in(b) to correspond to the diagram in (a), the belt of tan and the strike symbol should be rotated 25° clockwise. In (c), the plunge is the angle between the horizontal and the line in question, not between the vertical and the line in question.

p. 338, ‘‘Sculpting Mountains by Erosion’’ *(erratum)*
A hogback is slightly different from a cuesta. A cuesta has a steep cliff on one side and a gentle dip slope on the other; it is thus asymmetric. A hogback is also underlain by dipping strata, but the dip slope has approximately the same slope as the escarpment face; a hogback is thus topographically symmetrical.

CHAPTER 12: DEEP TIME: HOW OLD IS OLD?

p. 390, Figure 12.24, and references elsewhere in text *(errata)*
The time scale is always being revised as new data become available. The chart used in the book was based on a 1985 time scale. The latest (1999) time scale, provided by the Geological Society of America, has the following differences:

BOUNDARY	*DATE IN FIG. 12.24*	*NEW DATE*
Oligocene/Eocene	36.6 Ma	33.7 Ma
Eocene/Paleocene	57.8 Ma	54.8 Ma
Jurassic/Triassic	208 Ma	206 Ma
Triassic/Permian	245 Ma	248 Ma
Permian/Carboniferous	286 Ma	290 Ma
Carboniferous/Devonian	360 Ma	354 Ma
Devonian/Silurian	408 Ma	417 Ma
Silurian/Ordovician	440 Ma	443 Ma

CHAPTER 13 — BIOGRAPHY OF EARTH

p. 403, Figure 13.11a, b *(erratum)*
The block of crust labeled "Congo" in part (a) and ‘‘W. Congo’’ in part (b) should be labeled "W. Africa." In other words, this block is the West African craton. There is no such thing as the "West Congo craton."

p. 414, line 12 *(clarification)*
The sentence that begins, "Thus, more of the oceanic crust. . .'' should read, ''Thus, at a given time in the Cretaceous, more of the oceanic crust was young and warm than is the case on Earth today."

CHAPTER 15 — RICHES IN ROCK: MINERAL RESOURCES

p. 462, Figure 15.16b *(erratum)*
A horizontal tunnel in a mine is an adit, not "addit."

CHAPTER 16 — UNSAFE GROUND: ALNDSLIDES AND OTHER MASS MOVEMENTS

p. 500, A Case Study: Slumping in Southern California—Portuguese Bend Slide (*clarification*)
The text implies that the cause of the Portuguese Bend slump is largely a consequence of a rise in the water table due to a rise in the land surface. The detachment surface of the slide, caused by the presence of a layer of week bentonite (a clay formed from volcanic ash), already existed before development. Reactivation of movement on the slide surface was probably caused by an increase in subsurface fluid pressure caused by lawn watering and leaky cesspools. An increase in fluid pressure decreases the normal force across the sliding surface. The additional load of fill placed on top of the ground probably contributed to triggering movement by adding weight to the slide.

CHAPTER 18 — RESTLESS REALM: OCEANS AND COASTS

pp. 558-59, " The Tides Go Out. . .'' *(clarification, including contributions by Tom Henley)*
The explanation of tides in the text is misleading, because it incorrectly specifies the source of the centrifugal force that causes tidal bulges. The issue is reexamined here, to avoid confusion.

Tides result from the interaction between, on the one hand, the gravitational pull exerted by the Moon and Sun on the Earth and, on the other hand, the centrifugal force caused by the revolution of the Earth about the Earth-Moon system's center of mass, in the case of lunar tides, and around the Earth-Sun center of mass in the case of solar tides. The above sentence uses three terms from physics that may need further clarification before going on:

1) The **center of mass** for an object, or a group of objects taken together, is the average position of the total mass. To picture the center of mass, think of two children of different weights sitting on a seesaw, at an equal distance from the pivot point. The seesaw tilts down in the direction of the heavier child, because the center of mass of the two children together is closer to that child. But if the heavier child moves closer toward the pivot, so that the center of mass of the two children lies directly over the pivot, then the seesaw will balance.

2) The **Earth-Moon system** refers to the Earth and Moon together. Contrary to what many people assume, the center of the Earth itself does not follow a smooth orbital

trajectory (an ellipse) around the Sun. Rather, it is the *center of mass* of the Earth-Moon system that follows this trajectory. As the Earth-Moon system orbits the Sun, it resembles two dancers, one heavy and one light, holding hands, facing each other and whirling in a circle as they move across the room (Fig. 1). Because the Earth is eighty-one times more massive than the Moon, the center of mass of the Earth-Moon system actually lies 1700 km below the surface of the Earth (4,670 km out from the center of the Earth),

3) We use the term **centrifugal force** here, because our reference frame is the moving Earth—centrifugal force is the outward-directed force acting on an object in or on an orbiting object. In the case of the Earth-Moon system, it is **centripetal force**, an inward directed force defined with respect to a fixed external reference frame, that keeps the bodies from flying off into space as the system orbits the center of mass. But with respect to the Earth, which is orbiting the center of mass of the Earth-Moon system, the water on the Earth feels a centrifugal force causing it to move outward. Please seen the errata and addenda for p. 25 of Chapter 1 for further clarification of centrifugal and centripetal force.

Our discussion below focuses on lunar tides. The revolution of the Earth around the Earth-Moon system's center of mass generates centrifugal forces on both the Earth and Moon that would cause the Earth and Moon to fly away from each other were it not for the gravitational attraction holding them together. To picture this phenomenon, let's look at the dancer analogy again; note that the center of mass of the pair of dancers in Figure 1 follows a straight-line trajectory. As they move, the dancers orbit their combined center of mass. At all times, each dancer feels a centrifugal force; if they were to let go of each other, they would fly outward. (Note, we could also say that a centripetal force, provided by the muscles in their arms, is holding the dancers together.) The centrifugal force acting on each dancer points outward, away from the partner (parallel to the dancers' outstretched arms), and is the same for all points on a dancer--thus, a dancer's nose feels the same centrifugal force as his or her ears. We can represent the direction and magnitude of the centrifugal force by an arrow (a vector) that points parallel to the imaginary line that connects the centers of each dancer and passes through the center of mass. All of the centrifugal force vectors have the same length (where the length of the vector represents the magnitude of the force).

Now, let's call the dancers Earth and Moon. Centrifugal force vectors all point away from the Moon (Fig. 2a). But centrifugal force is not the only force acting in this system. According to Newton's law of gravity, one object exerts a gravitational attraction on another object; the size of this attraction depends on the mass of the objects and on the distance between them. Thus, the Earth and Moon exert a gravitational attraction on each other. The arrows (vectors) represent the magnitude and direction of the Moon's gravitational pull at any point on the surface of the Earth. They point toward the center of the Moon. In order for the Earth to remain in orbit around the Earth-Moon system's center of mass, the Moon's gravitational attraction at the center of the Earth must exactly balance the centrifugal force at the center of the Earth. Furthermore, the Moon exerts more attraction on the near side of the Earth than at Earth's center, and less attraction on the far side of the Earth than at Earth's center. Thus, the combination of centrifugal force and gravitational force produces outward forces on both sides of the Earth.

So, in summary, the ocean feels both the force of gravity that results from the Moon's attraction, and the centrifugal force that results from the rotation of the Earth-Moon system around its center of mass. If we draw the vectors representing these two forces on a cross section of the Earth, we see that the vectors representing centrifugal force do not have the same length as those representing gravitational attraction, except at the Earth's center, and moreover they do not point in the same direction as the vectors representing gravitational attraction (Fig. 2a). The force that the ocean water feels is the sum of the two forces acting on the water. You can determine the sum by drawing the vectors so they touch head to tail--the sum is the vector that completes the triangle (see the inset of Fig. 2b). This sum is called the **tide-generating force**.

Tides are caused by the tide-generating force. On the near side of the Earth, gravitational vectors are larger than centrifugal force vectors; thus, adding the two vectors leaves a net tide-generating force that pulls the sea surface toward the Moon, making the surface of the sea bulge toward the Moon. On the far side of the Earth, centrifugal force vectors are larger than gravitational vectors, so centrifugal force caused by the orbiting of the Earth-Moon system around the center of mass causes the surface of the sea to bulge outward, away from the Moon (Fig. 2c). Notice that this effect has nothing to do with the spinning of the Earth on its axis--this spin has no measurable effect on the sea surface.

Tides rise and fall at a given location during the day because the Earth spins beneath these two tidal bulges. Since the Earth spins completely once a day, the simple model described above (sometimes referred to as the **equilibrium theory of tides**) predicts two high tides and two low tides at a given point per day. (Since the Moon is also progressing in its twenty-eight-day orbit around the Earth, we don't quite get to the second tide in twenty-four hours.) Since the spin axis is not perpendicular to the plane of the Earth-Moon system, a given point passes between a high part of one bulge during one part of the day and a lower part of the other bulge during another part of the day, so the two high tides at a location are not the same size (Fig. 2c). The magnitude of tides also varies with the seasons, because the Sun also exerts gravitational attraction. But even though it is much more massive than the Moon, the Sun is so far away that its role in causing tides is only 46% that of the Moon. (The Sun's effect on tides is covered in the book.) Note that tide-generating forces also affect the solid rock of Earth's crust, but the rock is to strong to rise and fall significantly.

This discussion has imagined a very simple Earth, with no continents and no friction. But in reality, friction interferes with the movement of ocean waters in response to tide-generating forces, continents block water movements, and the shapes of seas, bays, and basins affect how the sea surface responds to these forces. Such complications are addressed by the **dynamic theory of tides**. This theory explains why different regions have different patterns of tides and why tidal range varies so much around the Earth—but a fuller discussion is beyond the scope of this book.

CHAPTER 19 — A HIDDEN RESERVE: GROUNDWATER

p. 587, ‘‘Topography of the Water Table’’ *(clarification)*

Groundwater mimics the shape of the land surface in regions where the ground has relatively low permeability and a fairly abundant supply of water. If the ground is very permeable, or a great deal of time passes between successive rainfalls, then the water table has time to sink beneath hills and can become nearly flat.

pp. 587-88, “ Groundwater Flow” *(clarification)*

The statement that groundwater flows from high pressure toward low pressure is oversimplified. It is more correct to say that groundwater flows from *high head* to *low head*.

p. 589, ''Darcy's Law'' *(erratum)*

The hydraulic gradient is defined in the text as the difference in hydraulic head between two points divided by the horizontal distance between the two points. In fact, the hydraulic gradient is defined as the difference in hydraulic head divided by the distance along the flow path between the two points. Since the flow path between two points may be curved, the denominator of the equation is longer than the horizontal distance between two points. The hydraulic gradient is only approximately the slope of the water table.

CHAPTER 20 — AN ENVELOPE OF GAS: EARTH'S ATMOSPHERE AND CLIMATE

p. 639, Fig. 20.34 *(erratum)*

Northern Norway is not subtropical; the southern limit of tundra should extend farther to the west.

CHAPTER 22 —AMAZING ICE: GLACIERS AND ICE AGES

p. 673, Fig. 22.10b (*erratum*)

The velocity of flow of the ice should be given in "m per year" (not "m per second").

CHAPTER 23 — GLOBAL CHANGE IN THE EARTH SYSTEM

p. 709, Fig. 23.3c (erratum)

The photograph of the Earth is backward.

APPENDIX A — SCIENTIFIC BACKGROUND: MATTER AND ENERGY

p. A-3, Figure a.3 *(erratum)*

The distinction between classes of elements is incorrect on this periodic table. The elements Al, Ga, In, Ti, Sn, Pb, and Bi are metals. B, Si, Ge, As, Sb, Te, Po, and At are sometimes called metalloids.

p. A-9, " The Forces of Nature" *(erratum)*

The weak nuclear force is responsible for the decay of certain nuclei; it does not hold particles together. Specifically, the weak nuclear force governs beta decay of neutrons—during beta decay, a neutron breaks apart to form a proton, an electron, and another particle called an antineutrino.

p. A-10, "Fission and Fusion" *(clarification)*

Technically, neutron decay (the splitting off of an electron so that the neutron becomes a proton) is not a type of fission. But it is a way in which a radioactive atom decays.