
THE ADVENTURES OF GEO, VOL. 1
THE INCREDIBLE
PLATE TECTONICS
COMIC
KANANI K.M. LEE
& ADAM WALLENTA

The Incredible Plate Tectonics Comic

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ISBN-10: 1-59327-549-8
ISBN-13: 978-1-59327-549-5

Publisher: William Pollock
Production Editor: Riley Hoffman
Cover Design: Ryan Byarlay
Developmental Editor: Tyler Ortman
Technical Reviewer: Callan Bentley
Copyeditor: Katie Grim
Compositor: Riley Hoffman
Proofreader: Paula L. Fleming

For information on distribution, translations, or bulk sales, please contact No Starch Press, Inc. directly:

No Starch Press, Inc.
245 8th Street, San Francisco, CA 94103
phone: 415.863.9900; info@nostarch.com; www.nostarch.com

Library of Congress Cataloging-in-Publication Data

Lee, Kanani K. M., author.
The incredible plate tectonics comic / Kanani K.M. Lee and Adam Wallenta.
pages cm. -- (The adventures of Geo ; Vol. 1)
Summary: "An introduction to plate tectonics in comic-book format with a text follow-up and suggestions for hands-on projects. Discusses Pangea, earthquakes, tsunamis, volcanoes, seafloor spreading, and the Earth's core, mantle, and crust."-- Provided by publisher.
Audience: Ages 8+
ISBN 978-1-59327-549-5 -- ISBN 1-59327-549-8
1. Plate tectonics--Comic books, strips, etc. 2. Plate tectonics--Juvenile literature. 3. Geology--Comic books, strips, etc. 4. Geology--Juvenile literature. 5. Graphic novels. I. Wallenta, Adam, author. II. Title.
QE511.4.L465 2014
551.1'36--dc23
2014016201

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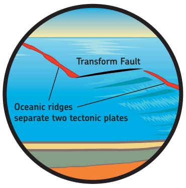
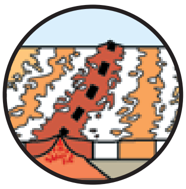
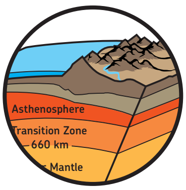

Transform Fault
Oceanic ridges
separate two tectonic plates




Asthenosphere
660 km
Mantle

ABOUT THE AUTHORS

Dr. Kanani K.M. Lee is an associate professor in the Department of Geology & Geophysics at Yale University, where she conducts experiments at high pressures and high temperatures, re-creating the conditions of the Earth's mantle and core in order to better understand the formation and evolution of the Earth and other planets.

Adam Wallenta has illustrated dozens of books and has worked for companies such as Marvel Comics, DC Entertainment, and Skyhorse Publishing. His diverse work can be seen at *www.adamwallenta.com*.

Kanani Lee and Adam Wallenta live near New Haven, Connecticut, with their son.

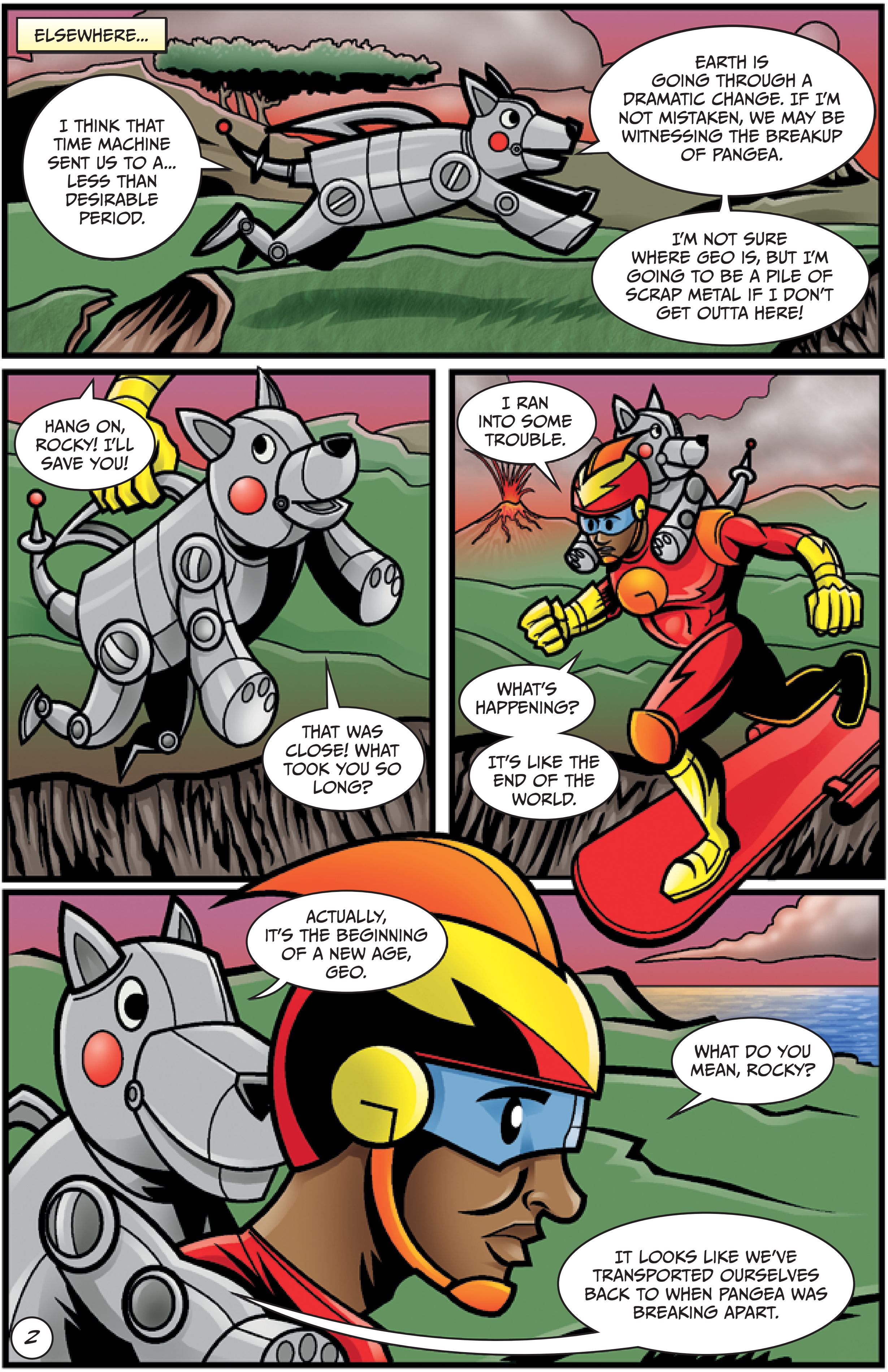
ACKNOWLEDGMENTS

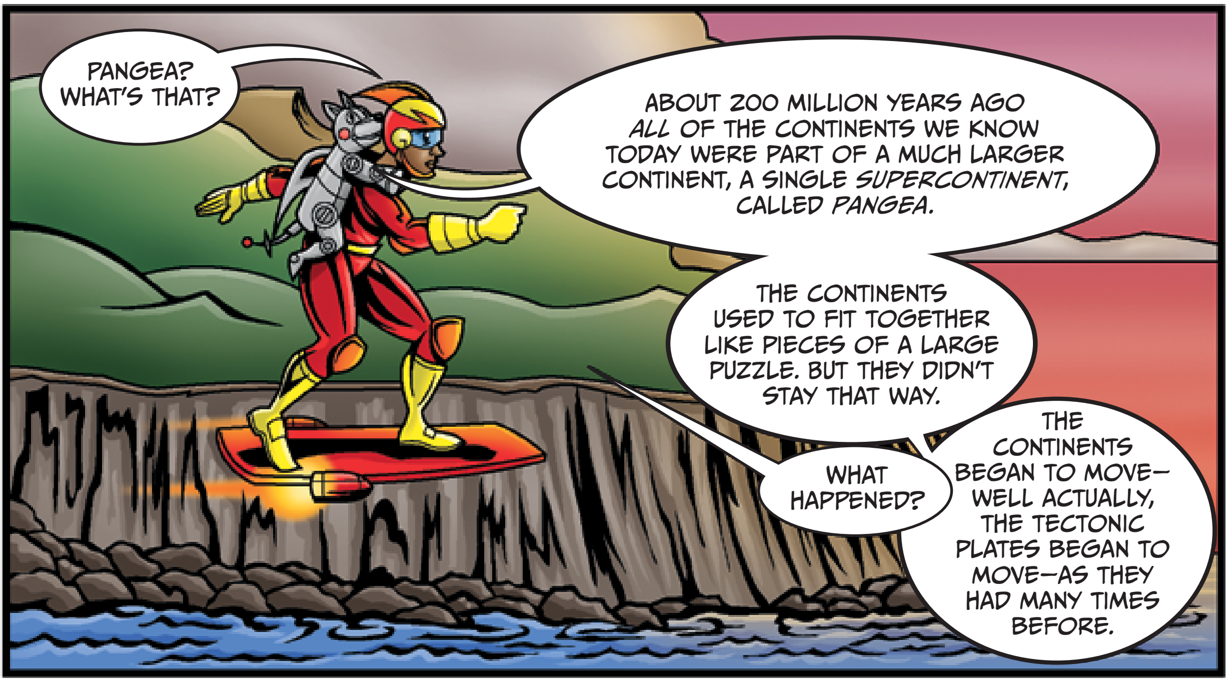
This book was originally produced with funds from the National Science Foundation as part of an NSF CAREER grant (EAR-0955824) awarded to Dr. Kanani K.M. Lee of Yale University.

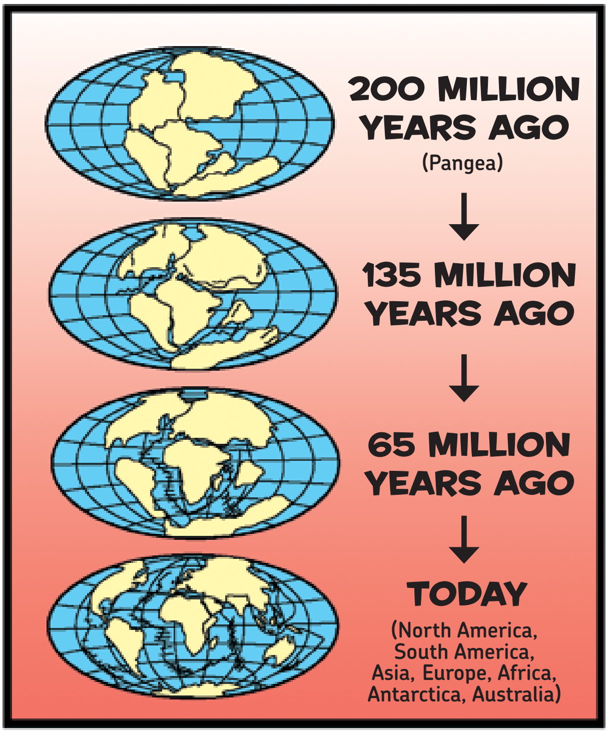
Dr. Lee thanks her Yale University colleagues Dr. David Bercovici and Dr. David A.D. Evans and New Haven Public Schools teachers Claire Hogue and Regina Melendez for their thorough reading of early drafts. Any mistakes, however, are solely those of Dr. Lee.

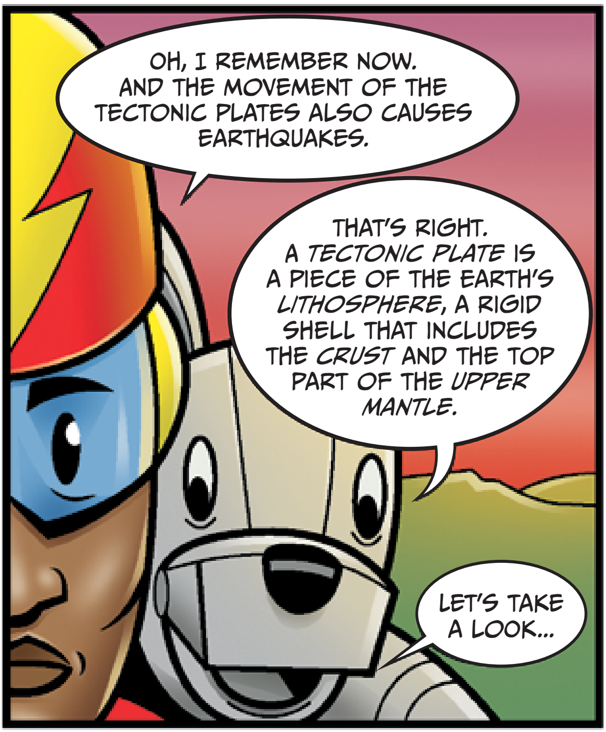
Adam Wallenta thanks Michael Nigro for his assistance and Roy Opochinski for lending an extra pair of eyes.


TWO HUNDRED MILLION YEARS AGO EARTH WAS VERY DIFFERENT.
IN THIS AGE OF UPHEAVAL WE FIND OUR HERO, GEO...
WHAT HAVE I GOTTEN MYSELF INTO NOW?

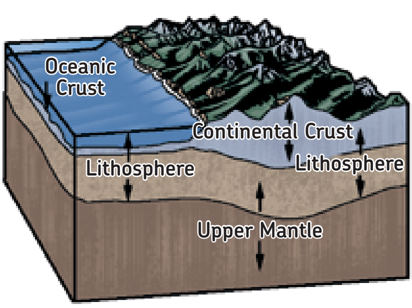

ELSEWHERE...
I THINK THAT TIME MACHINE SENT US TO A... LESS THAN DESIRABLE PERIOD.
EARTH IS GOING THROUGH A DRAMATIC CHANGE. IF I'M NOT MISTAKEN, WE MAY BE WITNESSING THE BREAKUP OF PANGEA.
I'M NOT SURE WHERE GEO IS, BUT I'M GOING TO BE A PILE OF SCRAP METAL IF I DON'T GET OUTTA HERE!
HANG ON, ROCKY! I'LL SAVE YOU!
THAT WAS CLOSE! WHAT TOOK YOU SO LONG?
I RAN INTO SOME TROUBLE.
WHAT'S HAPPENING?
IT'S LIKE THE END OF THE WORLD.
ACTUALLY, IT'S THE BEGINNING OF A NEW AGE, GEO.
WHAT DO YOU MEAN, ROCKY?
IT LOOKS LIKE WE'VE TRANSPORTED OURSELVES BACK TO WHEN PANGEA WAS BREAKING APART.

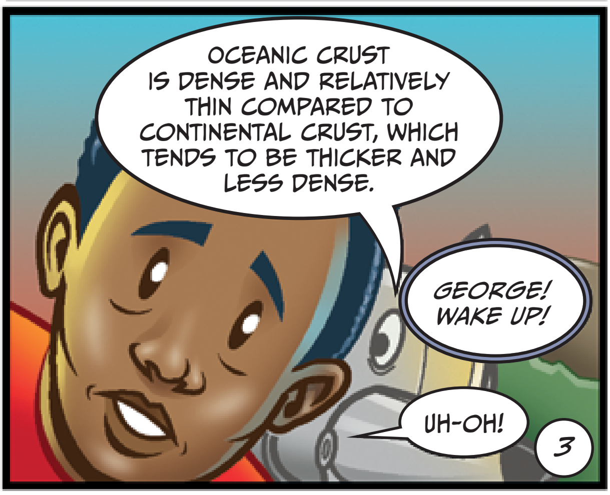


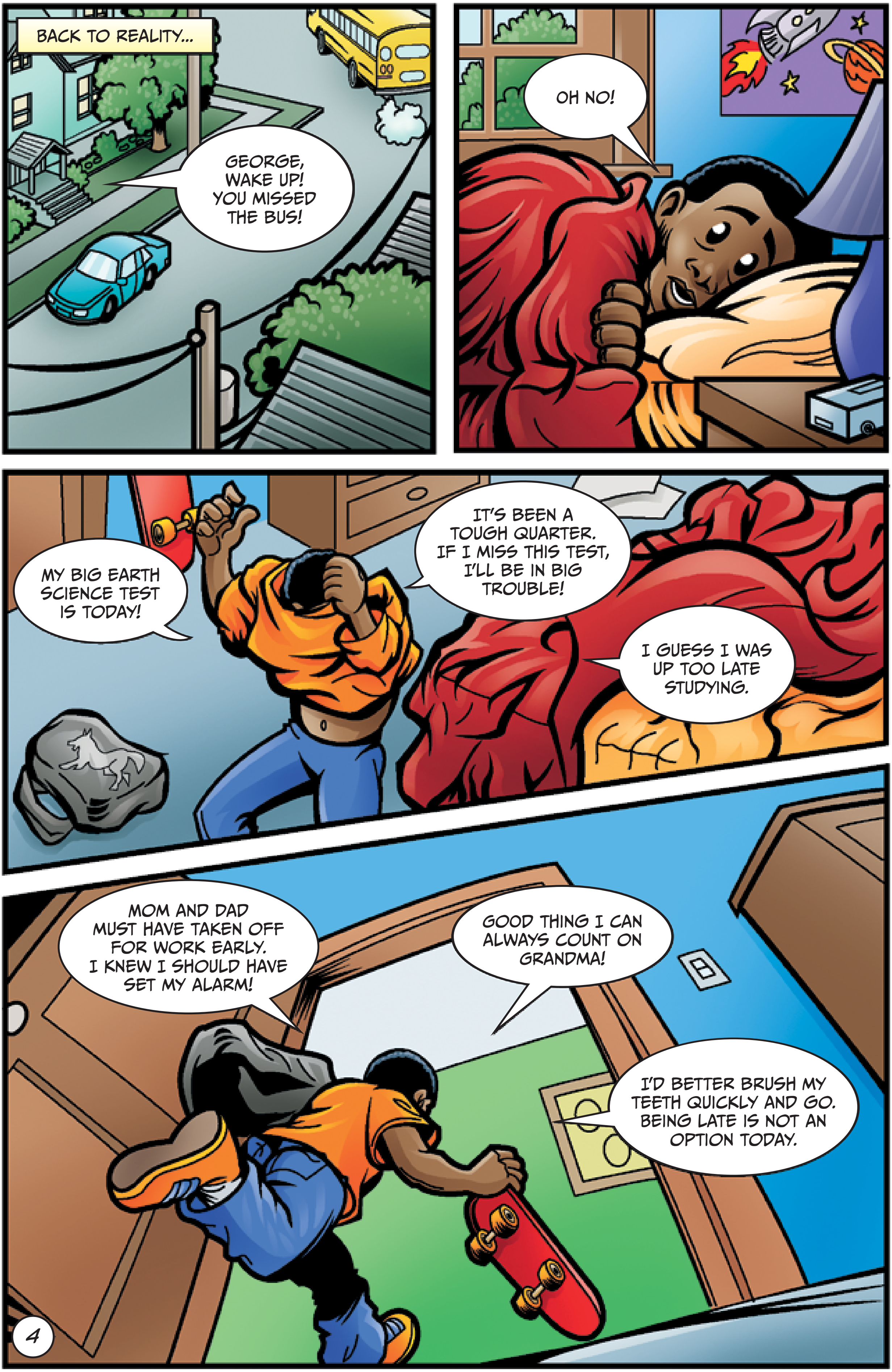




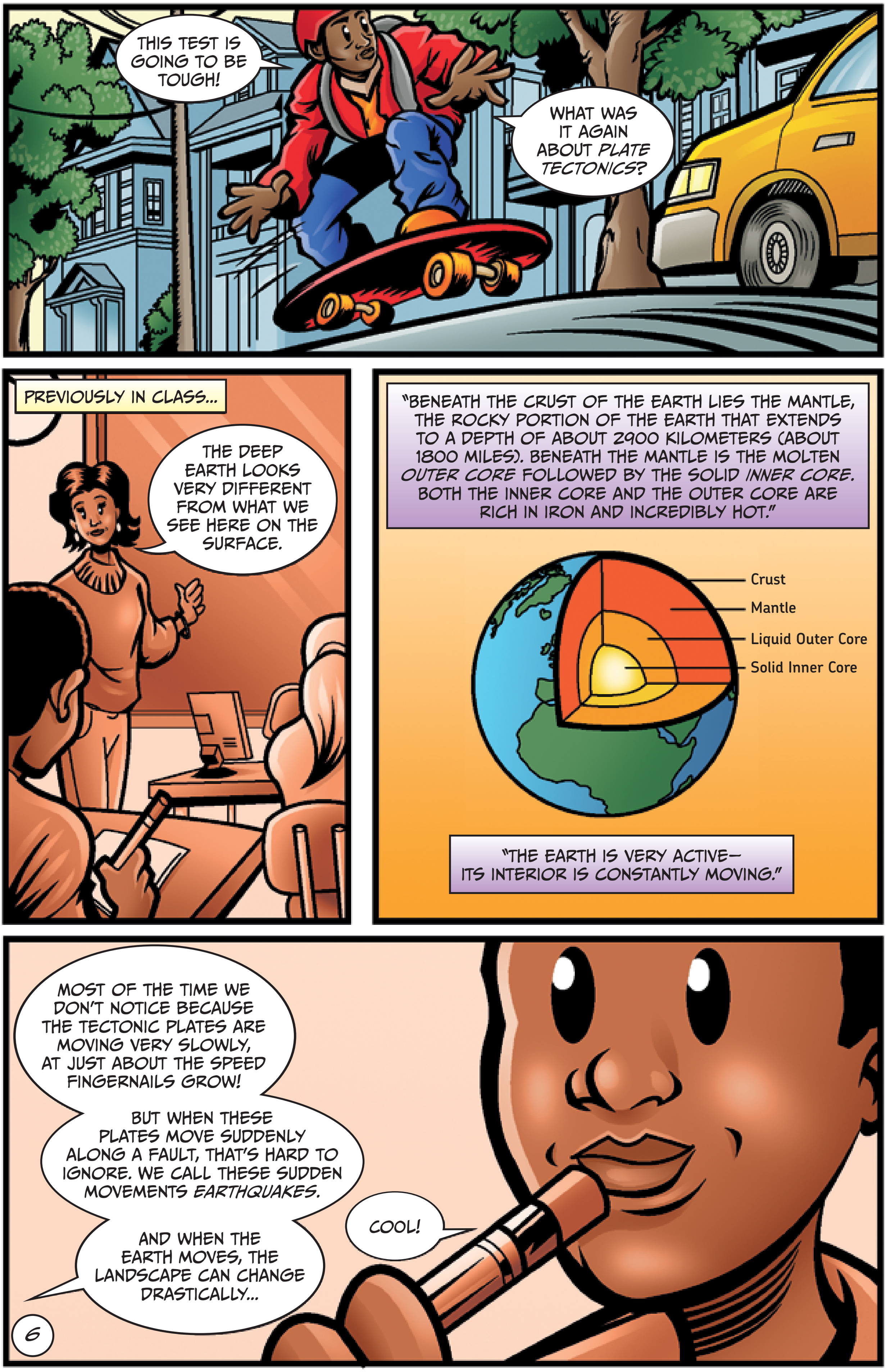
"*OCEANIC CRUST* IS THE CRUST UNDER THE OCEANS, WHEREAS *CONTINENTAL CRUST* IS WHAT THE CONTINENTS ARE MADE OF."





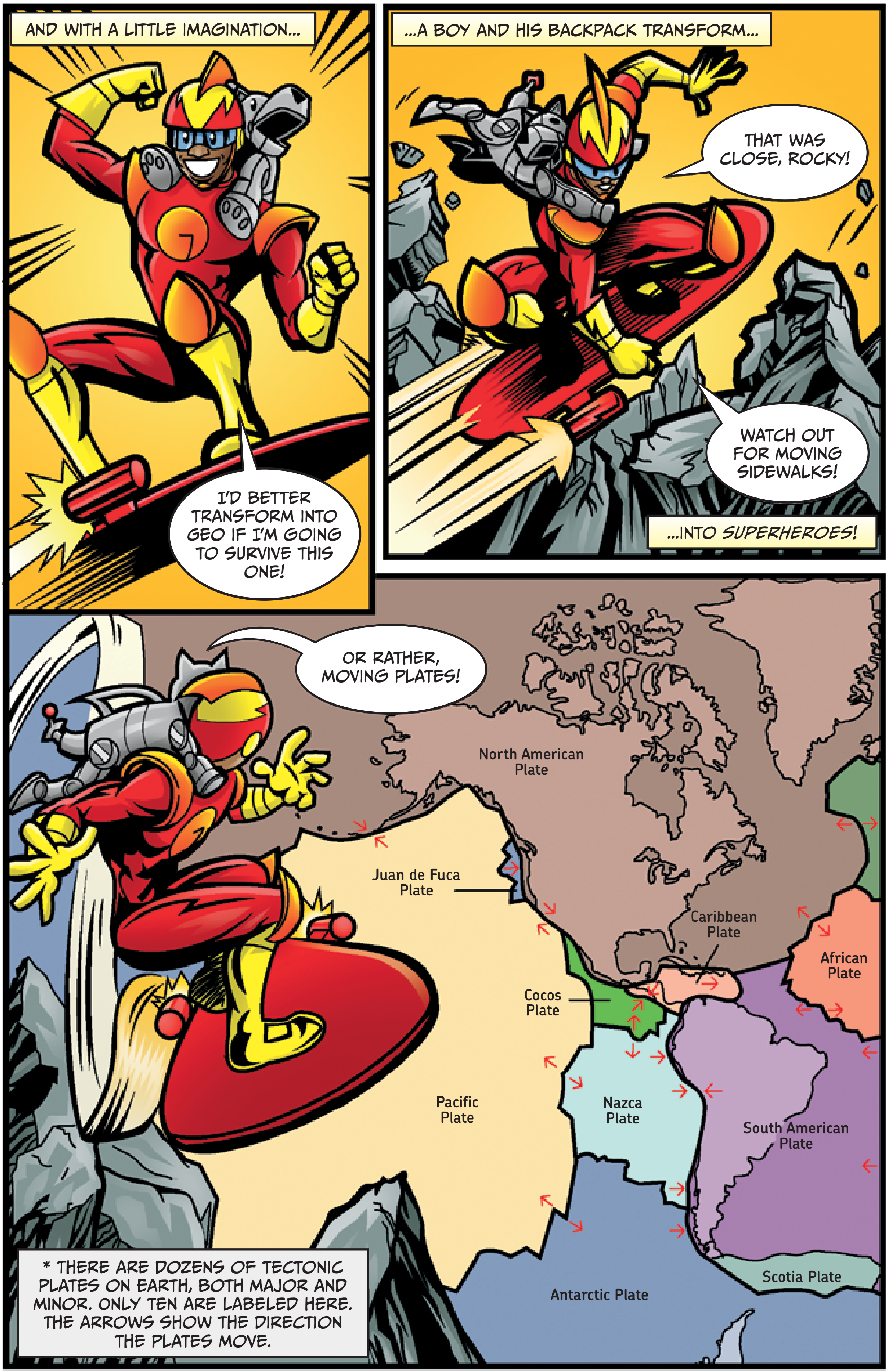

BACK TO REALITY...
GEORGE, WAKE UP! YOU MISSED THE BUS!
OH NO!
MY BIG EARTH SCIENCE TEST IS TODAY!
IT'S BEEN A TOUGH QUARTER. IF I MISS THIS TEST, I'LL BE IN BIG TROUBLE!
I GUESS I WAS UP TOO LATE STUDYING.
MOM AND DAD MUST HAVE TAKEN OFF FOR WORK EARLY. I KNEW I SHOULD HAVE SET MY ALARM!
GOOD THING I CAN ALWAYS COUNT ON GRANDMA!
I'D BETTER BRUSH MY TEETH QUICKLY AND GO. BEING LATE IS NOT AN OPTION TODAY.

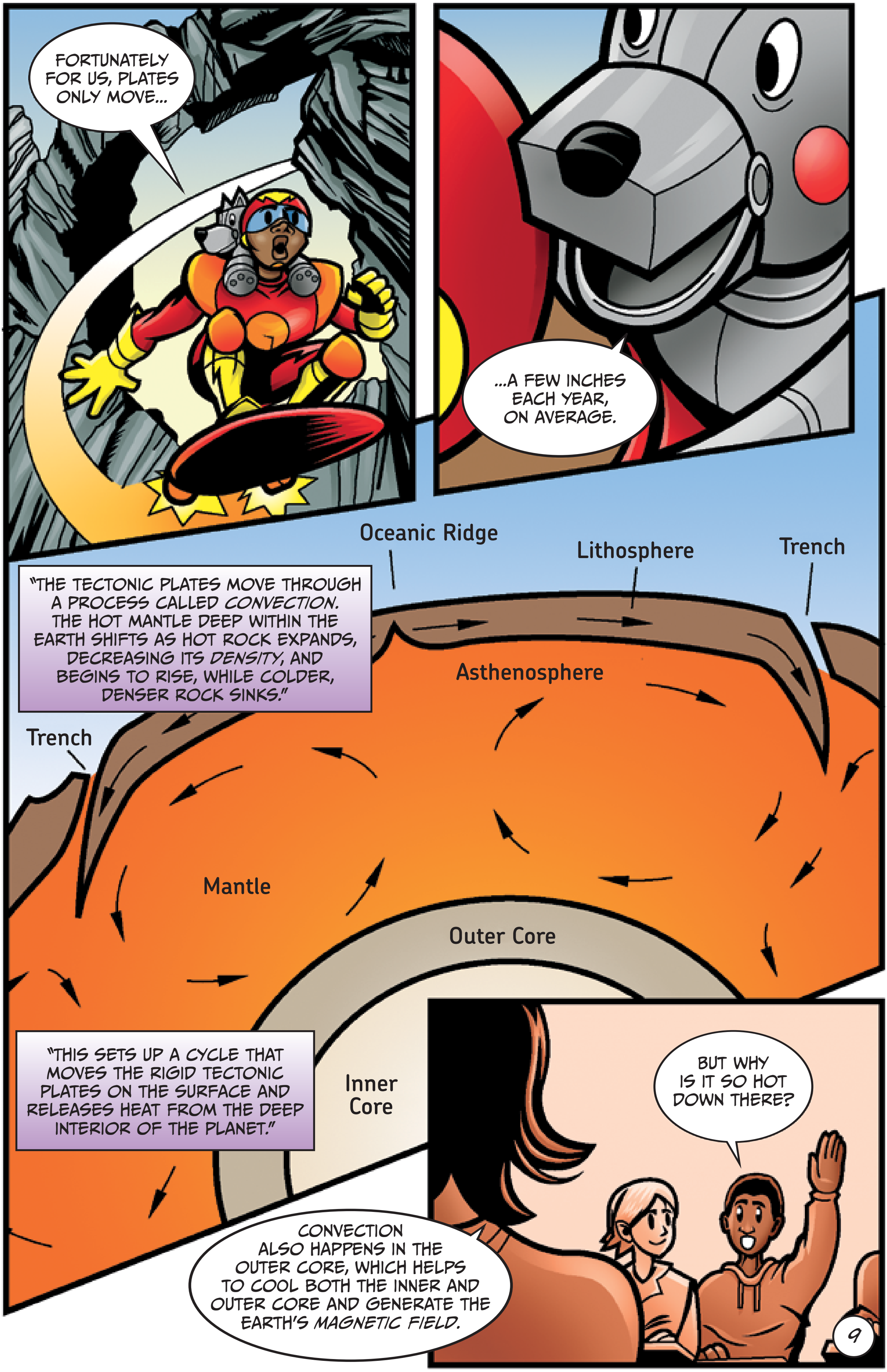

COME EAT SOME BREAKFAST, GEORGE. THEN I'LL DRIVE YOU TO SCHOOL.
YOU NEED A GOOD MEAL TO START THE DAY.
THANKS, GRANDMA! YOU'RE THE BEST! I'LL TAKE SOME TOAST FOR THE ROAD.
I HAVE A BIG TEST I CAN'T BE LATE FOR. I CAN'T GET STUCK IN TRAFFIC.
I'LL GET THERE QUICKER ON MY SKATEBOARD, ANYWAY.
YOU BE CAREFUL ON THAT THING, NOW.
OF COURSE, GRANDMA. I'M ALWAYS CAREFUL.
BESIDES... IT'S MY FAULT I OVERSLEPT.
I CAN EVEN QUIZ MYSELF ON THE WAY THERE—AND THE FRESH AIR WILL DO ME GOOD.
BYE, GRANDMA! I LOVE YOU! SEE YOU WHEN I GET HOME!
GOOD LUCK, BABY!



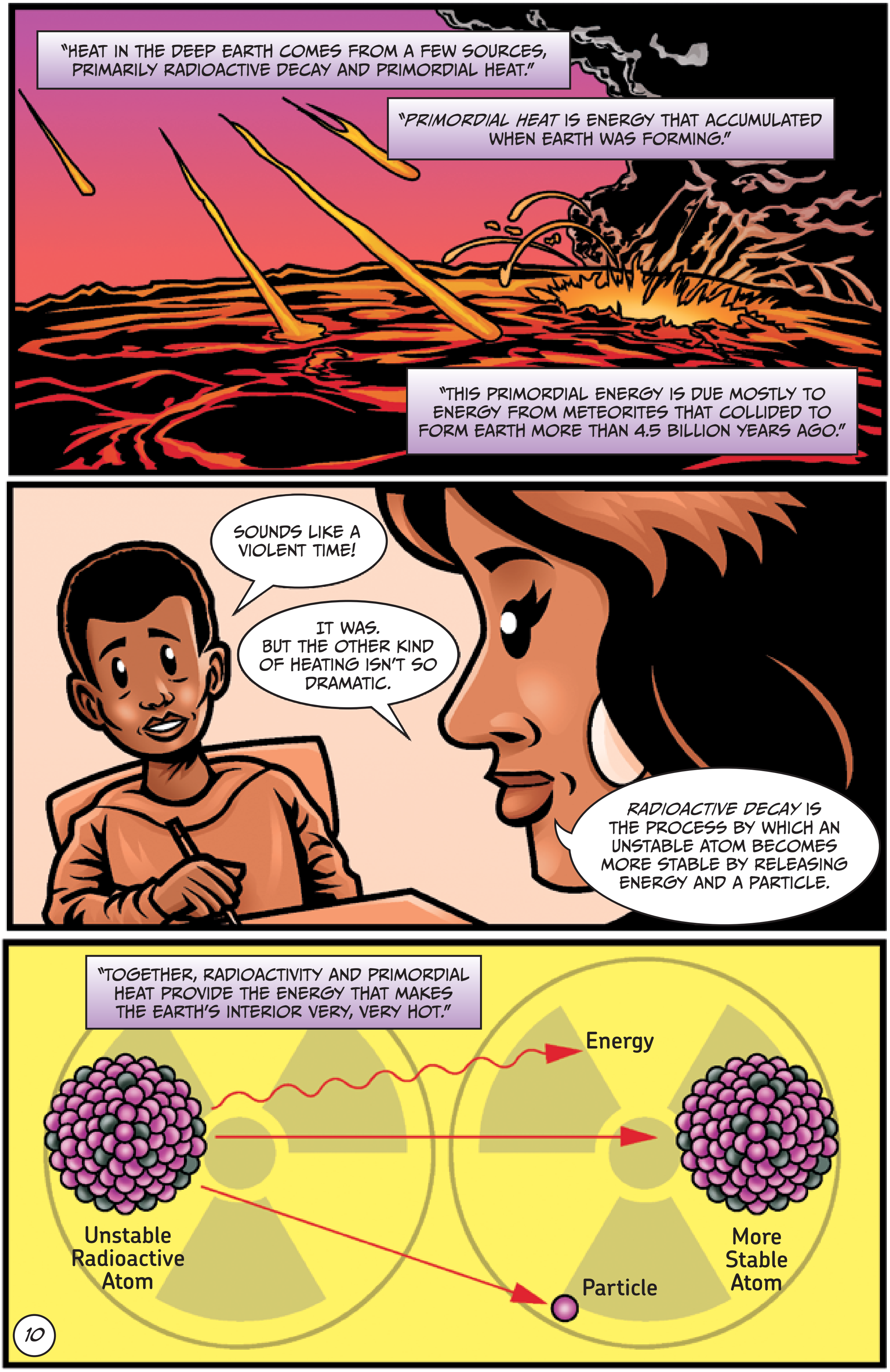
THIS TEST IS GOING TO BE TOUGH!
WHAT WAS IT AGAIN ABOUT PLATE TECTONICS?
PREVIOUSLY IN CLASS...
THE DEEP EARTH LOOKS VERY DIFFERENT FROM WHAT WE SEE HERE ON THE SURFACE.
"BENEATH THE CRUST OF THE EARTH LIES THE MANTLE, THE ROCKY PORTION OF THE EARTH THAT EXTENDS TO A DEPTH OF ABOUT 2900 KILOMETERS (ABOUT 1800 MILES). BENEATH THE MANTLE IS THE MOLTEN OUTER CORE FOLLOWED BY THE SOLID INNER CORE. BOTH THE INNER CORE AND THE OUTER CORE ARE RICH IN IRON AND INCREDIBLY HOT."
Crust
Mantle
Liquid Outer Core
Solid Inner Core
"THE EARTH IS VERY ACTIVE— ITS INTERIOR IS CONSTANTLY MOVING."
MOST OF THE TIME WE DON'T NOTICE BECAUSE THE TECTONIC PLATES ARE MOVING VERY SLOWLY, AT JUST ABOUT THE SPEED FINGERNAILS GROW!
BUT WHEN THESE PLATES MOVE SUDDENLY ALONG A FAULT, THAT'S HARD TO IGNORE. WE CALL THESE SUDDEN MOVEMENTS EARTHQUAKES.
AND WHEN THE EARTH MOVES, THE LANDSCAPE CAN CHANGE DRASTICALLY...
COOL!

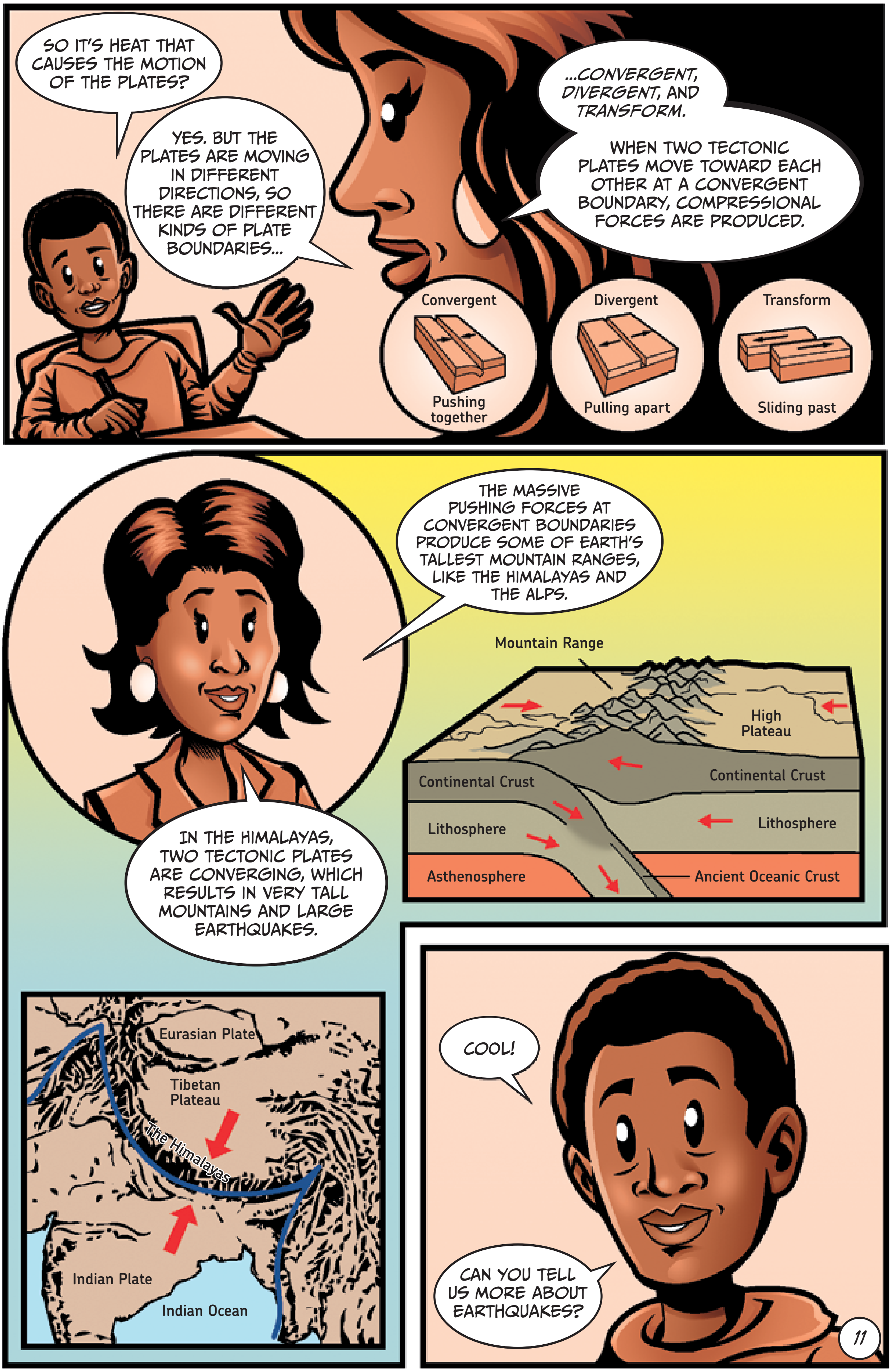

ON HIS WAY TO SCHOOL...
THESE SIDEWALKS ARE SO UNEVEN. I HAVE TO BE CAREFUL NOT TO FALL.
THESE CRACKS REMIND ME OF THE FAULTS WE TALKED ABOUT IN CLASS.
"*FAULTS* ARE FRACTURES OR CRACKS IN THE EARTH'S CRUST THAT FORM DURING AN EARTHQUAKE. WHEN THE TECTONIC PLATES MOVE, THE MOVEMENT STRESSES THE ROCKS, WHICH THEN SOMETIMES SNAP!"
SNAP OUT OF IT, GEORGE! IF I DON'T PAY ATTENTION, THE CRACKS ARE GOING TO SEND ME FLYING!

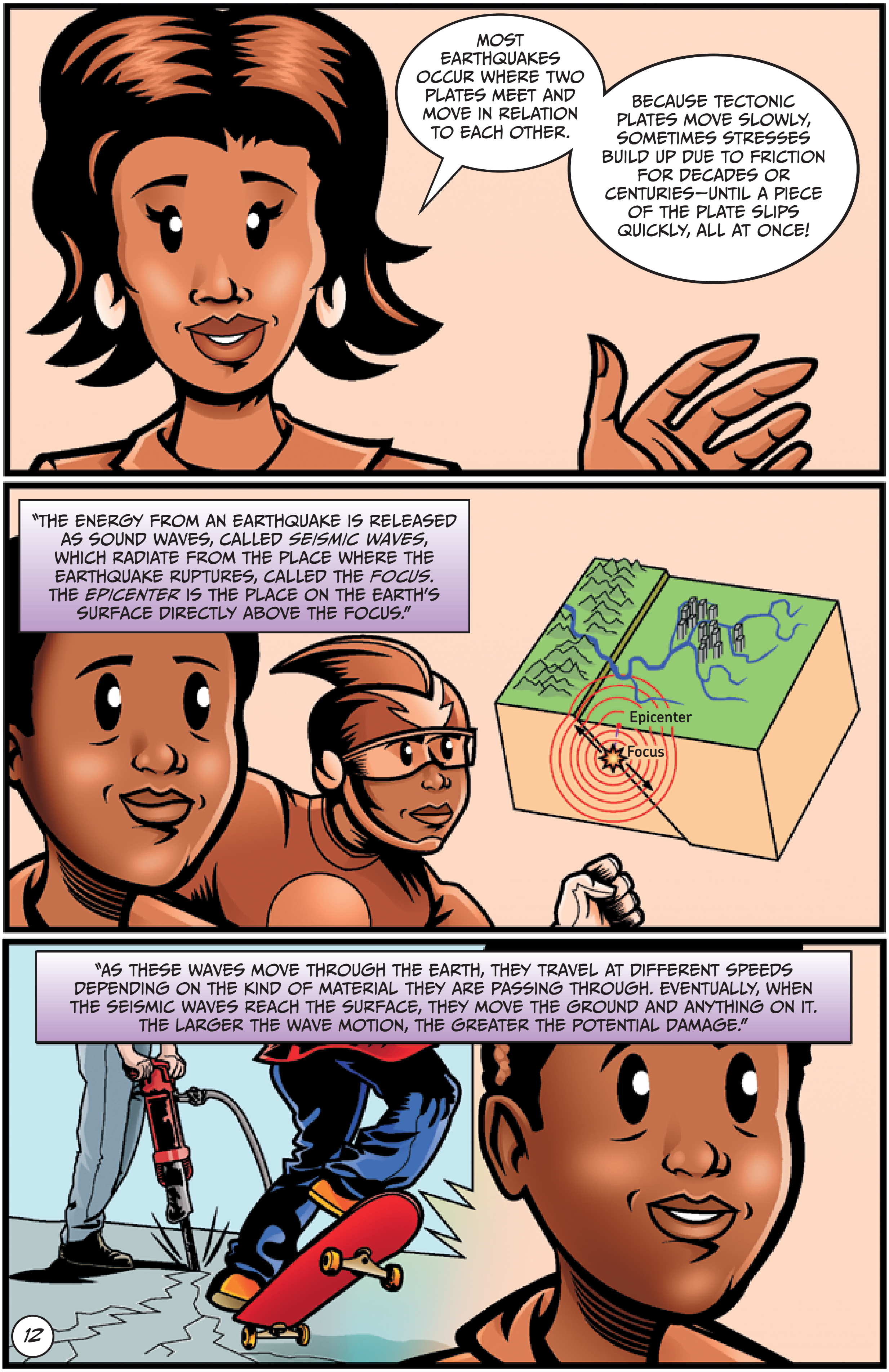

AND WITH A LITTLE IMAGINATION...
I'D BETTER TRANSFORM INTO GEO IF I'M GOING TO SURVIVE THIS ONE!
...A BOY AND HIS BACKPACK TRANSFORM...
THAT WAS CLOSE, ROCKY!
WATCH OUT FOR MOVING SIDEWALKS!
...INTO SUPERHEROES!
OR RATHER, MOVING PLATES!
North American Plate
Juan de Fuca Plate
Caribbean Plate
African Plate
Cocos Plate
Pacific Plate
Nazca Plate
South American Plate
Scotia Plate
Antarctic Plate
* THERE ARE DOZENS OF TECTONIC PLATES ON EARTH, BOTH MAJOR AND MINOR. ONLY TEN ARE LABELED HERE. THE ARROWS SHOW THE DIRECTION THE PLATES MOVE.



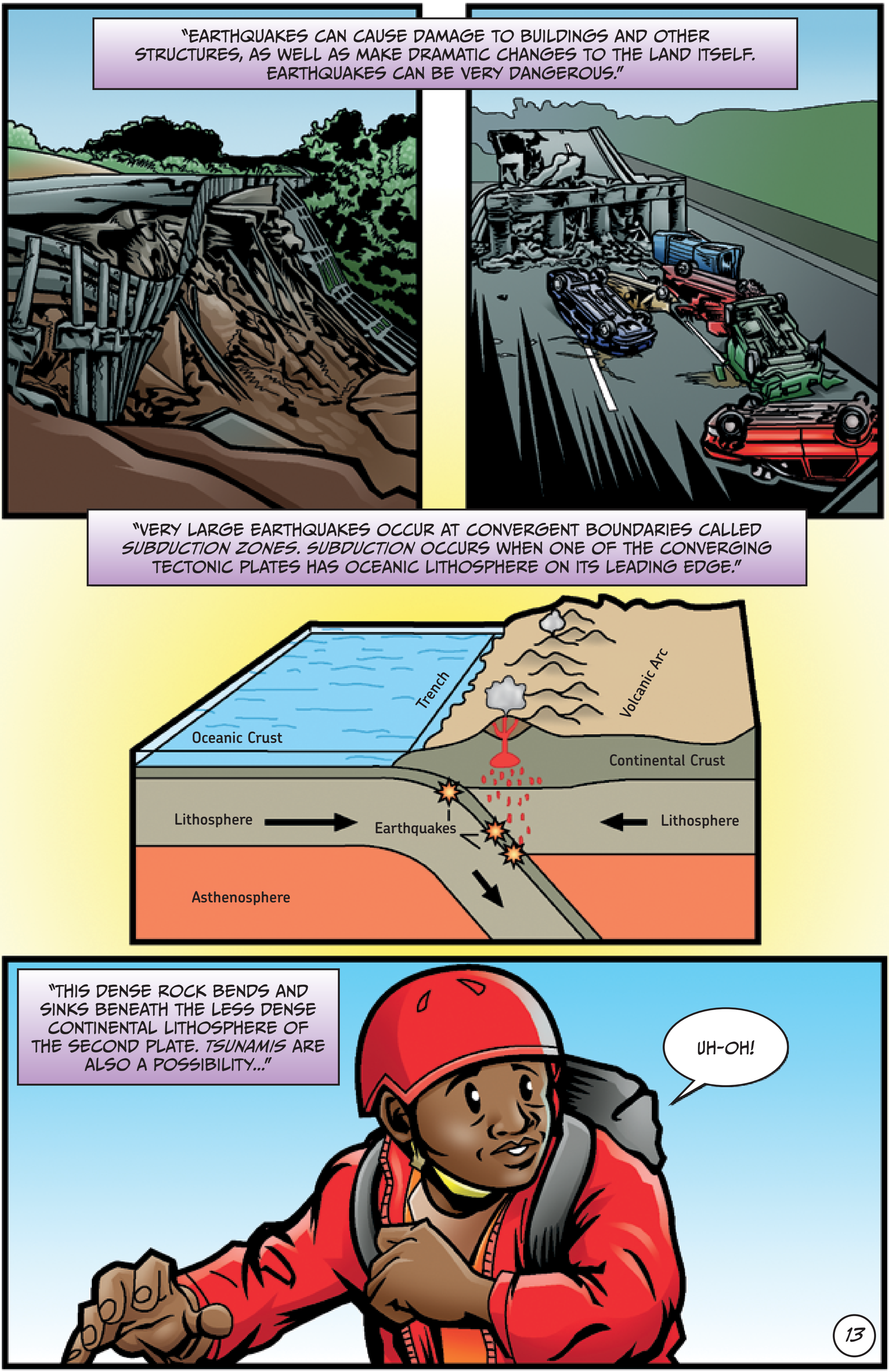
FORTUNATELY FOR US, PLATES ONLY MOVE...
...A FEW INCHES EACH YEAR, ON AVERAGE.
Oceanic Ridge
Lithosphere
Trench
"THE TECTONIC PLATES MOVE THROUGH A PROCESS CALLED *CONVECTION*. THE HOT MANTLE DEEP WITHIN THE EARTH SHIFTS AS HOT ROCK EXPANDS, DECREASING ITS *DENSITY*, AND BEGINS TO RISE, WHILE COLDER, DENSER ROCK SINKS."
Asthenosphere
Trench
Mantle
Outer Core
"THIS SETS UP A CYCLE THAT MOVES THE RIGID TECTONIC PLATES ON THE SURFACE AND RELEASES HEAT FROM THE DEEP INTERIOR OF THE PLANET."
Inner Core
BUT WHY IS IT SO HOT DOWN THERE?
CONVECTION ALSO HAPPENS IN THE OUTER CORE, WHICH HELPS TO COOL BOTH THE INNER AND OUTER CORE AND GENERATE THE EARTH'S *MAGNETIC FIELD*.


"HEAT IN THE DEEP EARTH COMES FROM A FEW SOURCES, PRIMARILY RADIOACTIVE DECAY AND PRIMORDIAL HEAT."
"*PRIMORDIAL HEAT* IS ENERGY THAT ACCUMULATED WHEN EARTH WAS FORMING."
"THIS PRIMORDIAL ENERGY IS DUE MOSTLY TO ENERGY FROM METEORITES THAT COLLIDED TO FORM EARTH MORE THAN 4.5 BILLION YEARS AGO."
SOUNDS LIKE A VIOLENT TIME!
IT WAS. BUT THE OTHER KIND OF HEATING ISN'T SO DRAMATIC.
RADIOACTIVE DECAY IS THE PROCESS BY WHICH AN UNSTABLE ATOM BECOMES MORE STABLE BY RELEASING ENERGY AND A PARTICLE.
"TOGETHER, RADIOACTIVITY AND PRIMORDIAL HEAT PROVIDE THE ENERGY THAT MAKES THE EARTH'S INTERIOR VERY, VERY HOT."
Energy
Unstable Radioactive Atom
More Stable Atom
Particle

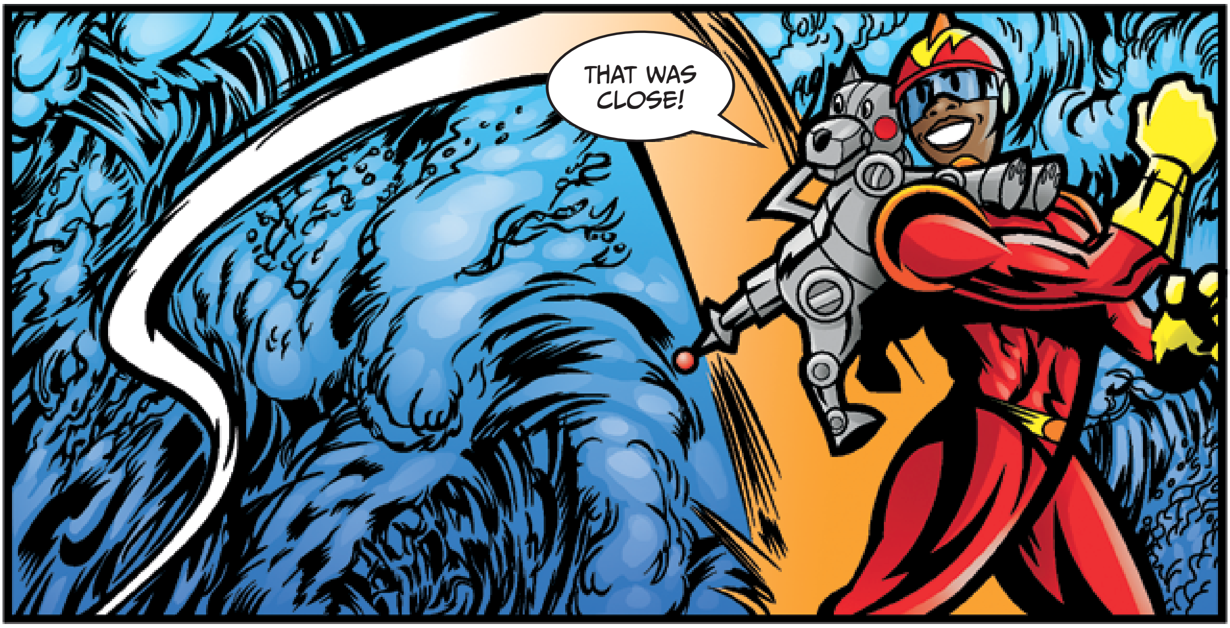

SO IT'S HEAT THAT CAUSES THE MOTION OF THE PLATES?
YES. BUT THE PLATES ARE MOVING IN DIFFERENT DIRECTIONS, SO THERE ARE DIFFERENT KINDS OF PLATE BOUNDARIES...
...CONVERGENT, DIVERGENT, AND TRANSFORM.
WHEN TWO TECTONIC PLATES MOVE TOWARD EACH OTHER AT A CONVERGENT BOUNDARY, COMPRESSIONAL FORCES ARE PRODUCED.
Convergent
Pushing together
Divergent
Pulling apart
Transform
Sliding past
THE MASSIVE PUSHING FORCES AT CONVERGENT BOUNDARIES PRODUCE SOME OF EARTH'S TALLEST MOUNTAIN RANGES, LIKE THE HIMALAYAS AND THE ALPS.
Mountain Range
High Plateau
Continental Crust
Continental Crust
Lithosphere
Lithosphere
Asthenosphere
Ancient Oceanic Crust
IN THE HIMALAYAS, TWO TECTONIC PLATES ARE CONVERGING, WHICH RESULTS IN VERY TALL MOUNTAINS AND LARGE EARTHQUAKES.
Eurasian Plate
Tibetan Plateau
The Himalayas
Indian Plate
Indian Ocean
COOL!
CAN YOU TELL US MORE ABOUT EARTHQUAKES?



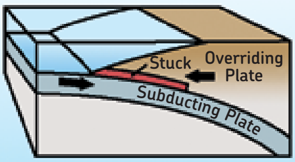
MOST EARTHQUAKES OCCUR WHERE TWO PLATES MEET AND MOVE IN RELATION TO EACH OTHER.
BECAUSE TECTONIC PLATES MOVE SLOWLY, SOMETIMES STRESSES BUILD UP DUE TO FRICTION FOR DECADES OR CENTURIES—UNTIL A PIECE OF THE PLATE SLIPS QUICKLY, ALL AT ONCE!
"THE ENERGY FROM AN EARTHQUAKE IS RELEASED AS SOUND WAVES, CALLED *SEISMIC WAVES*, WHICH RADIATE FROM THE PLACE WHERE THE EARTHQUAKE RUPTURES, CALLED THE *FOCUS*. THE *EPICENTER* IS THE PLACE ON THE EARTH'S SURFACE DIRECTLY ABOVE THE FOCUS."
Epicenter
Focus
"AS THESE WAVES MOVE THROUGH THE EARTH, THEY TRAVEL AT DIFFERENT SPEEDS DEPENDING ON THE KIND OF MATERIAL THEY ARE PASSING THROUGH. EVENTUALLY, WHEN THE SEISMIC WAVES REACH THE SURFACE, THEY MOVE THE GROUND AND ANYTHING ON IT. THE LARGER THE WAVE MOTION, THE GREATER THE POTENTIAL DAMAGE."


"EARTHQUAKES CAN CAUSE DAMAGE TO BUILDINGS AND OTHER STRUCTURES, AS WELL AS MAKE DRAMATIC CHANGES TO THE LAND ITSELF. EARTHQUAKES CAN BE VERY DANGEROUS."
"VERY LARGE EARTHQUAKES OCCUR AT CONVERGENT BOUNDARIES CALLED *SUBDUCTION ZONES. SUBDUCTION* OCCURS WHEN ONE OF THE CONVERGING TECTONIC PLATES HAS OCEANIC LITHOSPHERE ON ITS LEADING EDGE."
Trench
Volcanic Arc
Oceanic Crust
Continental Crust
Lithosphere
Earthquakes
Lithosphere
Asthenosphere
"THIS DENSE ROCK BENDS AND SINKS BENEATH THE LESS DENSE CONTINENTAL LITHOSPHERE OF THE SECOND PLATE. *TSUNAMIS* ARE ALSO A POSSIBILITY..."
UH-OH!

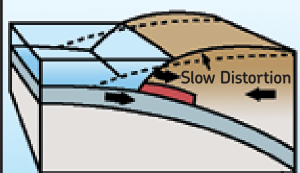

SUDDENLY...
AACK! I DON'T WANT TO GET WET!
TIME TO TRANSFORM!
TSUNAMIS ARE NO JOKE!



"TSUNAMIS OFTEN OCCUR AT SUBDUCTION ZONES WHERE THE DENSER OCEANIC LITHOSPHERE SINKS UNDER THE LESS DENSE CONTINENTAL LITHOSPHERE."



"FRICTION BETWEEN THE TWO PLATES CAN CAUSE THEM TO 'STICK,' MAKING THE TOP PLATE BULGE UNDER THE STRAIN."

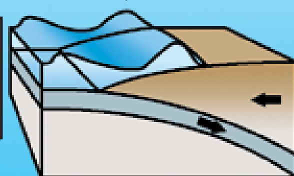


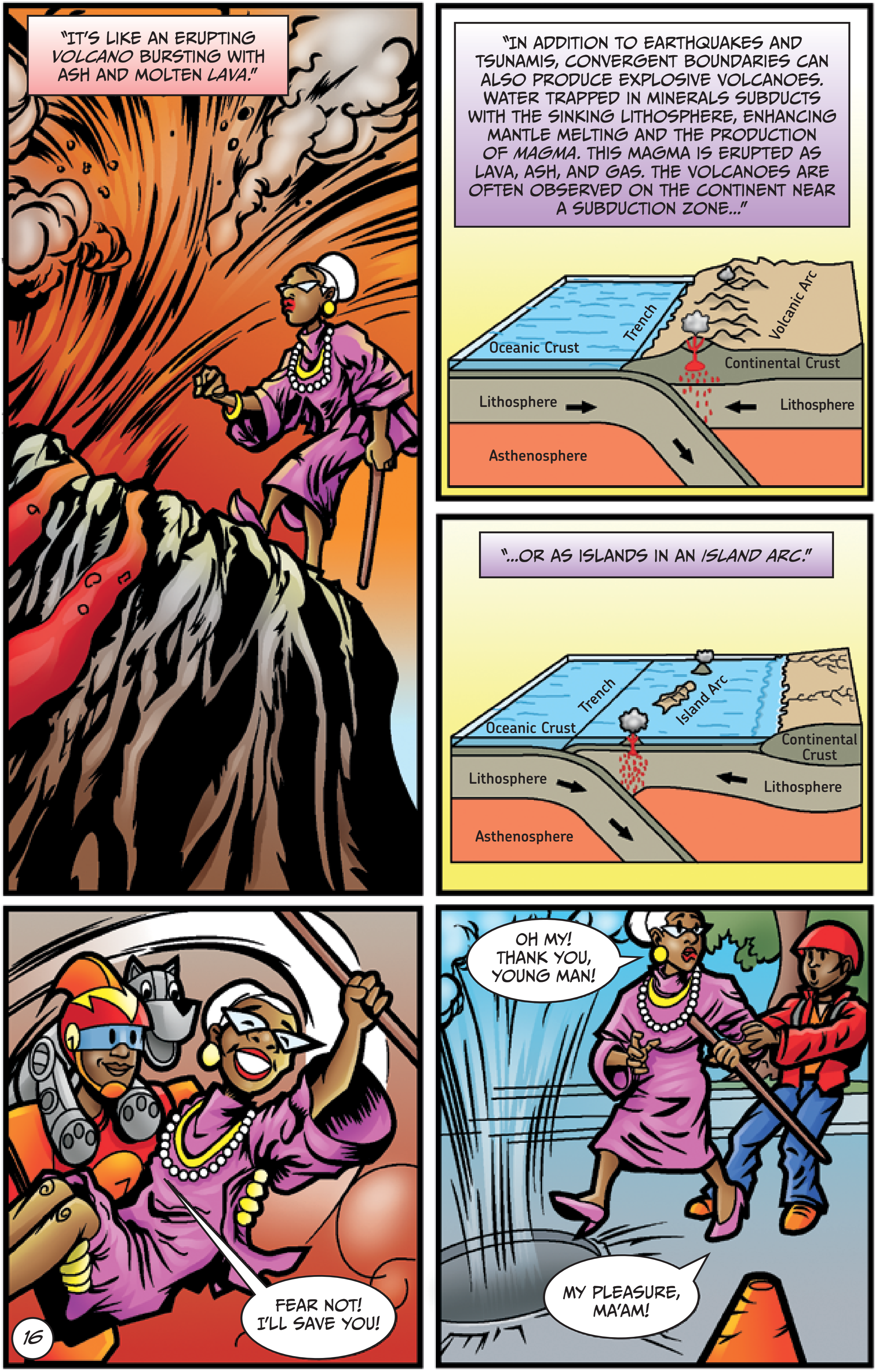
"WHEN AN EARTHQUAKE OCCURS, THE PLATES SLIP AND RELEASE ENERGY INTO THE WATER."

Tsunami starts during earthquake

"THIS ENERGY RELEASE PRODUCES THE TSUNAMI WAVES."

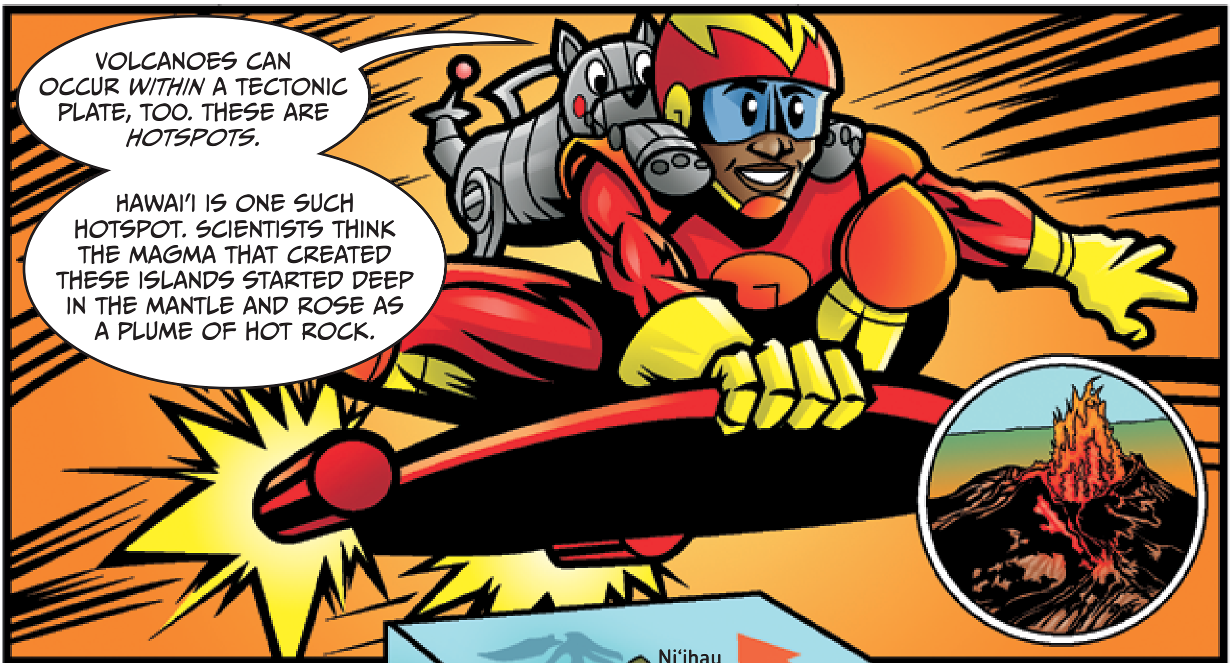
Tsunami waves spread



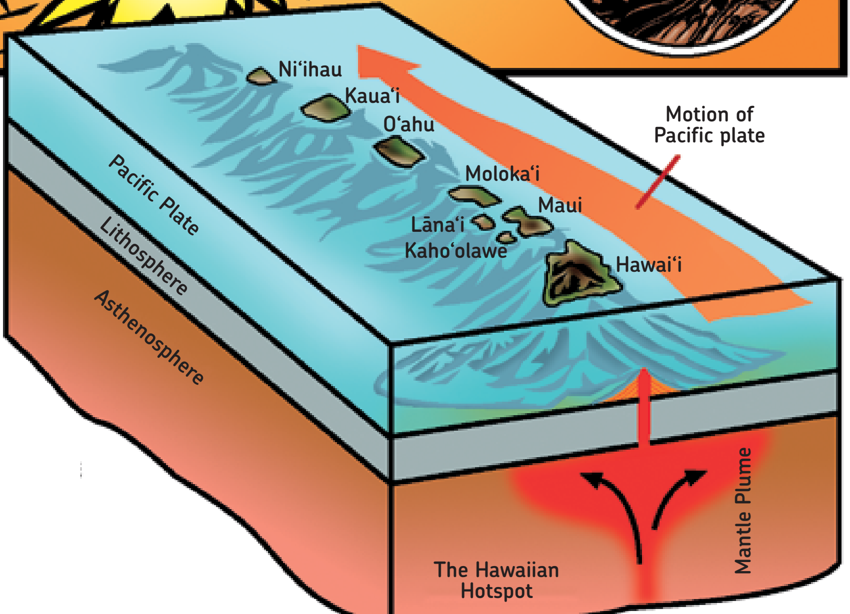

"IT'S LIKE AN ERUPTING VOLCANO BURSTING WITH ASH AND MOLTEN LAVA."
"IN ADDITION TO EARTHQUAKES AND TSUNAMIS, CONVERGENT BOUNDARIES CAN ALSO PRODUCE EXPLOSIVE VOLCANOES. WATER TRAPPED IN MINERALS SUBDUCTS WITH THE SINKING LITHOSPHERE, ENHANCING MANTLE MELTING AND THE PRODUCTION OF MAGMA. THIS MAGMA IS ERUPTED AS LAVA, ASH, AND GAS. THE VOLCANOES ARE OFTEN OBSERVED ON THE CONTINENT NEAR A SUBDUCTION ZONE..."
Oceanic Crust
Trench
Volcanic Arc
Continental Crust
Lithosphere
Lithosphere
Asthenosphere
"...OR AS ISLANDS IN AN ISLAND ARC."
Trench
Island Arc
Oceanic Crust
Continental Crust
Lithosphere
Lithosphere
Asthenosphere
FEAR NOT! I'LL SAVE YOU!
16
OH MY! THANK YOU, YOUNG MAN!
MY PLEASURE, MA'AM!

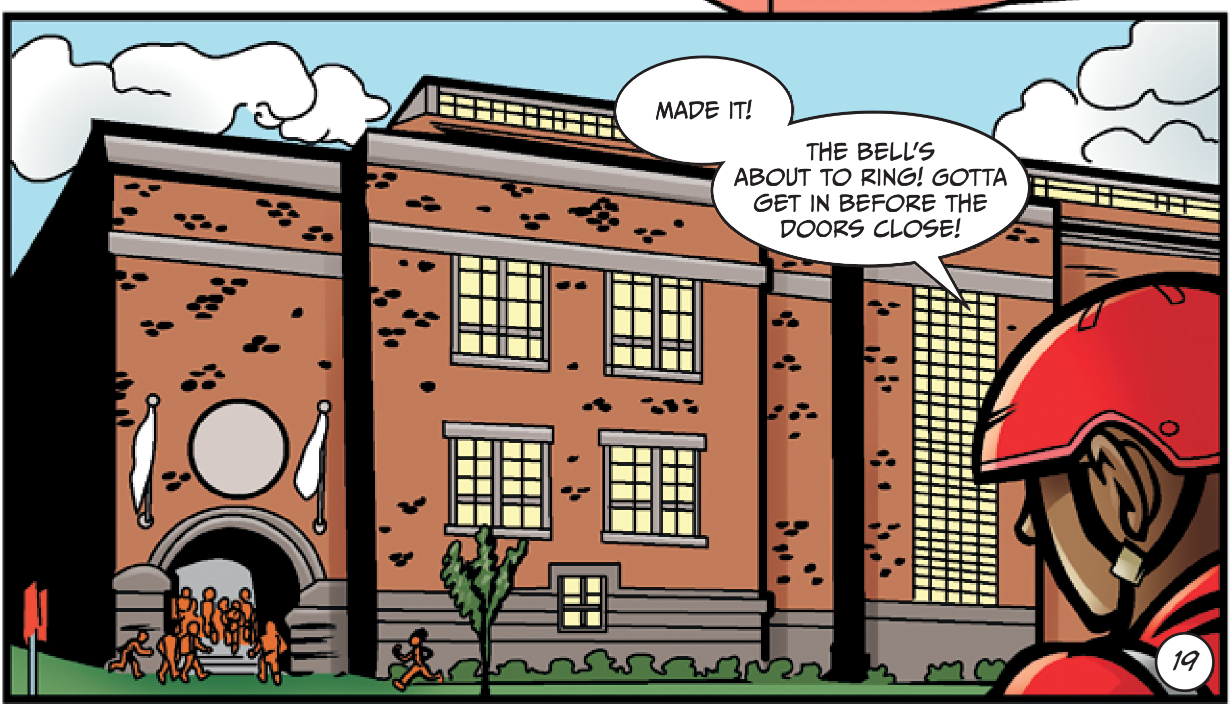
GOTTA RUN!
RING OF FIRE
Aleutian Trench
Kuril Trench
Japan Trench
Izu Ogasawara Trench
Ryukyu Trench
Philippine Trench
Mt. Pinatubo
Mt. Mayon
Marianas Trench
Bougainville Trench
Java Trench
Tonga Trench
Kermadec Trench
PACIFIC OCEAN
Cascadia Trench
Mt. Garibaldi
Mt. St. Helens
Middle America Trench
Peru-Chile Trench
"THE *RING OF FIRE* IS THE BOUNDARY SURROUNDING THE PACIFIC OCEAN WHERE MANY TECTONIC PLATES MEET AND MOVE AGAINST ONE ANOTHER."
"THE RING OF FIRE HAS AREAS OF SUBDUCTION AT EACH OF ITS *TRENCHES*, ALONG WITH ARC VOLCANOES ALONG THE BOUNDARIES. THESE VOLCANOES ARE HOW THIS REGION GETS ITS NAME."
"IN FACT, NEARLY ALL VOLCANIC ERUPTIONS HAPPEN ALONG PLATE BOUNDARIES."

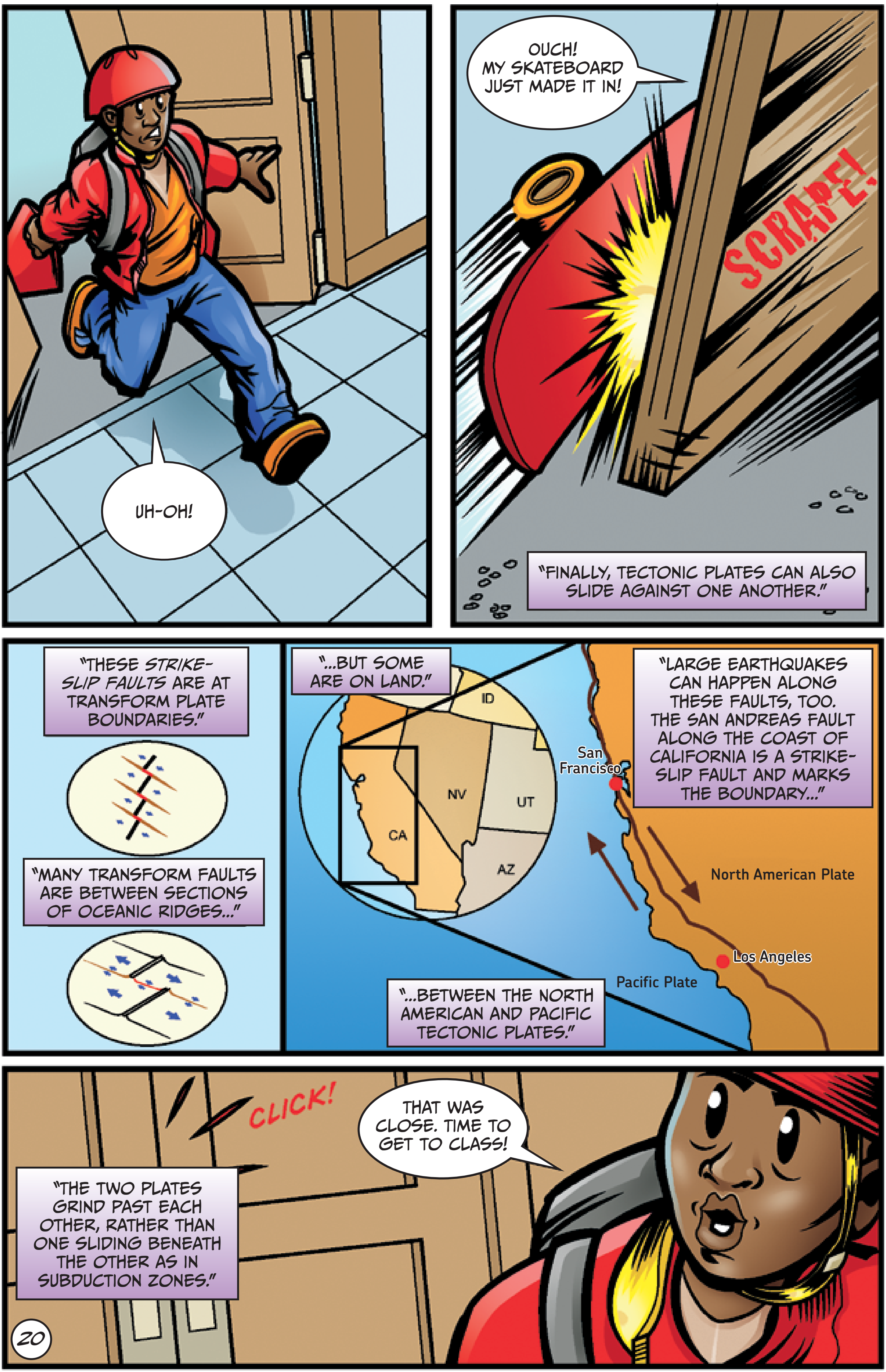

"NOT ALL VOLCANOES ARE DESTRUCTIVE. AT DIVERGENT BOUNDARIES, WHERE PLATES MOVE APART, NEW CRUST IS MADE. HERE, OCEANIC PLATES SPREAD APART AND NEW ROCK IS FORMED AT THE BOTTOM OF THE OCEAN. THIS IS CALLED *SEAFLOOR SPREADING.*"
"IN FACT, MOST VOLCANIC ERUPTIONS ON EARTH OCCUR AT THESE *OCEANIC RIDGES* WHERE THE SEAFLOOR SPREADS. ANYWHERE THERE IS AN ACTIVE VOLCANO, HEAT FROM DEEP IN THE EARTH IS ESCAPING."
Magnetic stripes recorded at oceanic ridge
Lithosphere
Magma
"NOT ONLY DOES THIS MAGMA MAKE NEW ROCK, THE IRON-RICH MINERALS IN IT RECORD EARTH'S MAGNETIC FIELD AS THEY COOL...
HEY, KID! WATCH OUT! YOU CAN'T RIDE ON THIS!
"...LEAVING A RECORD OF THE MAGNETIC FIELD ALONG THE OCEAN FLOOR. THE FARTHER FROM THE OCEANIC RIDGE A PIECE OF THE OCEANIC CRUST IS, THE OLDER IT IS."
UH-OH!



"AS THE PACIFIC TECTONIC PLATE MOVED IN A NORTHWEST DIRECTION, NEW ISLANDS WERE FORMED. THE OLDEST ISLANDS ARE NI'IHAU AND KAUA'I, WHICH STOPPED ERUPTING 5 MILLION YEARS AGO. THE YOUNGEST—AND STILL ACTIVELY ERUPTING—IS THE 'BIG ISLAND' OF HAWAI'I. GIVEN THE AGE OF THE ROCKS ON EACH ISLAND AND THE DISTANCE BETWEEN THEM, SCIENTISTS HAVE MEASURED THE AVERAGE SPEED OF THE PACIFIC PLATE TO BE APPROXIMATELY 10 CENTIMETERS (ABOUT 4 INCHES) PER YEAR."

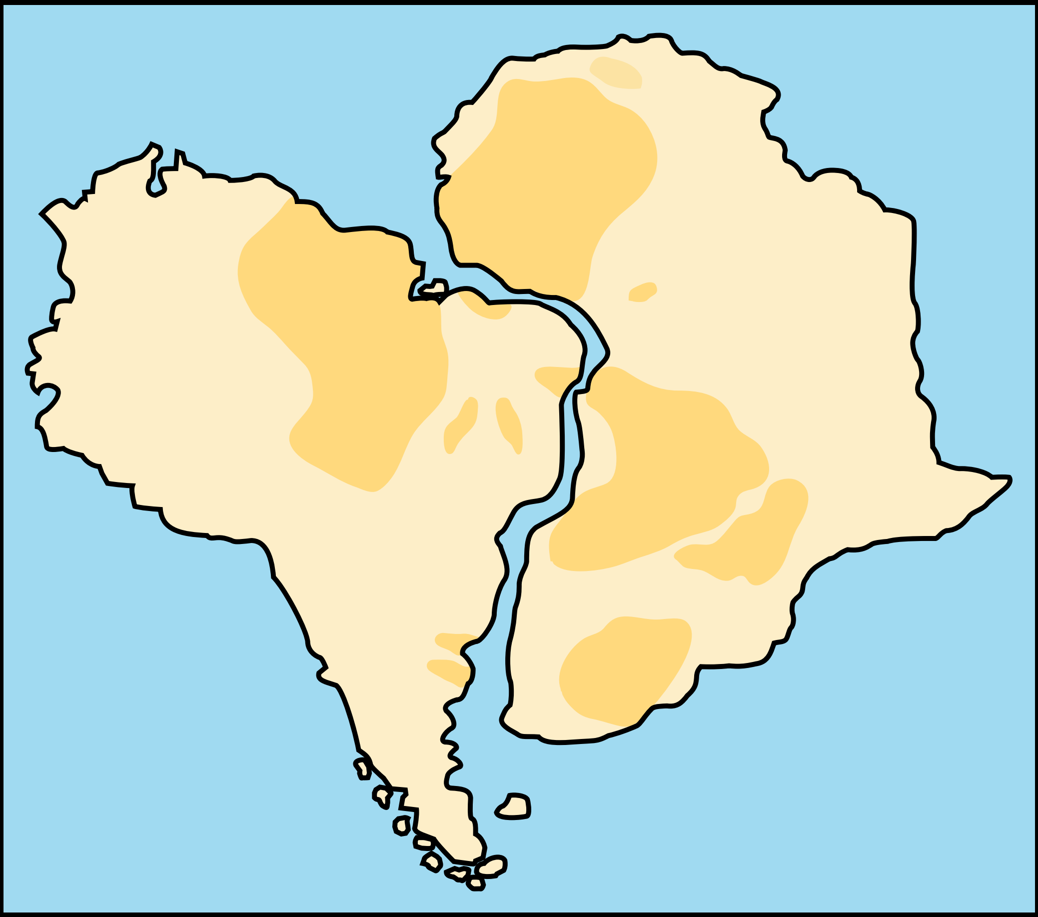





UH-OH!
OUCH! MY SKATEBOARD JUST MADE IT IN!
SCRAPE!
"FINALLY, TECTONIC PLATES CAN ALSO SLIDE AGAINST ONE ANOTHER."
"THESE STRIKE-SLIP FAULTS ARE AT TRANSFORM PLATE BOUNDARIES."
"MANY TRANSFORM FAULTS ARE BETWEEN SECTIONS OF OCEANIC RIDGES..."
"...BUT SOME ARE ON LAND."
ID
NV
UT
CA
AZ
San Francisco
"LARGE EARTHQUAKES CAN HAPPEN ALONG THESE FAULTS, TOO. THE SAN ANDREAS FAULT ALONG THE COAST OF CALIFORNIA IS A STRIKE-SLIP FAULT AND MARKS THE BOUNDARY..."
North American Plate
Los Angeles
Pacific Plate
"...BETWEEN THE NORTH AMERICAN AND PACIFIC TECTONIC PLATES."
CLICK!
THAT WAS CLOSE. TIME TO GET TO CLASS!
"THE TWO PLATES GRIND PAST EACH OTHER, RATHER THAN ONE SLIDING BENEATH THE OTHER AS IN SUBDUCTION ZONES."


...YOU'LL HAVE EXACTLY 45 MINUTES TO FINISH THE TEST.
LOOKS LIKE I JUST MADE IT.
DON'T FORGET TO WRITE YOUR NAME ON ALL SHEETS, PLEASE.
ALL RIGHT, CLASS, YOU CAN GET STARTED.
SUBDUCTION. I KNOW WHAT THAT IS!
TSUNAMIS...
...PLATE TECTONICS...
...FAULTS...
...MANTLE...
45 MINUTES LATER...
HOW DID YOU DO?
NOT SURE. BUT I FEEL PRETTY GOOD.


THE NEXT DAY...
I CAN'T WAIT TO SEE WHAT I GOT ON THE SCIENCE TEST.
I'M STARTING TO FEEL A LITTLE NERVOUS.
OH BOY.
GREAT JOB, GEORGE!
HUH?
100%
Great Job!
WOW! A PERFECT SCORE!
I GUESS ALL THAT STUDYING PAID OFF.
SURE DID!
THE END!



LIKE PUZZLE PIECES—PLATE TECTONICS

Ever notice how the east coast of South America looks like it would fit together pretty well with the west coast of Africa? Scientists, beginning in the late 1500s, noticed this too, along with some other puzzling discoveries (like how ancient fossils of the same species would show up in two distant continents, with no explanation as to how a creature could have hopped across an entire ocean from one continent to another).

But until the theory of *plate tectonics* came about, scientists didn't have a good explanation for these observations. The rocky crust of the Earth seems so clearly solid, rigid, and stationary, it didn't occur to observers that our planet's surface could move so dramatically—though it takes *millions* or even *billions* of years. It wasn't until the 1960s, with breakthroughs in studying the ocean floor, that the theory of plate tectonics had enough scientific evidence to catch on as an explanation for geological formations and events such as mountains, volcanoes, trenches, and earthquakes.

So what are *tectonic plates* anyway? They're interlocking pieces of the Earth's surface, made up of the crust plus the upper portion of the mantle. The plates vary in thickness and composition, and they can contain two different types of crust: *oceanic crust* and *continental crust*. Oceanic crust tends to be denser and thinner than its continental counterpart. The difference in density is due to the differing minerals that make up each crust. A single tectonic plate can contain both continental crust and oceanic crust.

SEAFLOOR SPREADING AND OTHER WONDERS IN THE OCEAN

What exactly was the evidence that led scientists to think that the Earth's surface is composed of plates? Scientists studied ridges at the bottom of the ocean, often called *mid-ocean ridges* (although they are not necessarily in the "middle" of an ocean). Lava erupts at these oceanic ridges, and geologists found that the rocks closest to the ridge were younger than those farther away.

This led scientists to think that the ridge wasn't *just* a ridge—it was actually a boundary between two tectonic plates! This process by which oceanic crust is formed at the ridge and slowly pushes out as newer crust continues to form is called *seafloor spreading*. The term for this meeting of two tectonic plates is *divergent boundary*, a formation in which two plates move *away* from each other and new rock is created.

Tectonic plates move slowly, at a speed ranging from 10 to 160 mm per year (about 1/2 inch to more than 6 inches per year). Over the course of millions of years, that distance adds up, and a piece of crust formed at a ridge can drift hundreds of kilometers (or hundreds of miles) away.

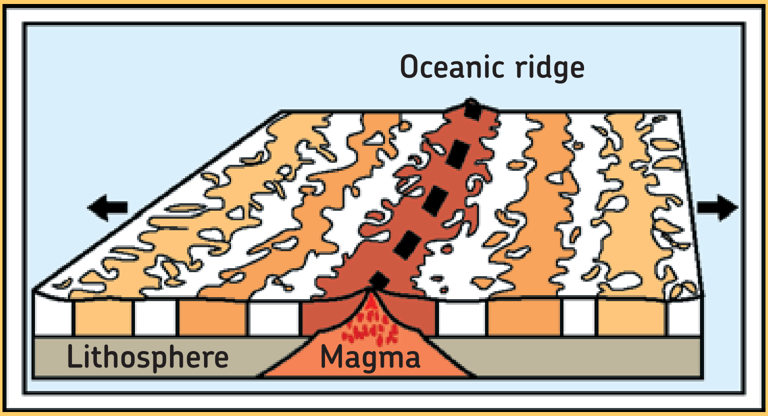
Geologists also make a special point to study *oceanic trenches*, deep chasms in the ocean floor created by tectonic plate motion at *convergent boundaries* (where plates move toward each other). At some convergent boundaries, we find a *subduction zone*, where one plate starts to bend down and slip below the other, creating a deep valley. These formations are the opposite of divergent boundaries—instead of new rock being created, rock is consumed as it enters the Earth's hot mantle. Chains of volcanoes parallel every subduction zone on Earth, suggesting that subduction causes melting and the production of magma.

The deepest and most famous oceanic trench is the Mariana Trench, located in the western Pacific Ocean just east of the Mariana Islands. It's more than 10 km (6 miles) deep and 69 km (43 miles) wide. It is nearly three times the average depth of the seafloor, which suggests that the forces bending the plate are immense!

WHAT ABOUT THOSE MAGNETS?

The Earth itself has a magnetic field (which is why the magnet in a compass needle points north). This magnetic field extends from the Earth's core outward. Right now, magnetic north isn't exactly true north—it's a few degrees off and is continually changing over time because the motion of liquid metal in the Earth's outer core generates the magnetic field. This type of magnetic field generation is called a *geodynamo*.

At random intervals (averaging several hundred thousand years), the Earth's magnetic field reverses (the north and south magnetic poles change places with each other). These reversals leave a record in cooling rocks that allows geologists to calculate past motion of continents and ocean floors as a result of plate tectonics.



Seafloor spreading produces new crust at oceanic ridges. The "stripes" in the figure indicate segments of new crust that have the same magnetic polarity. The farther a rock is from the oceanic ridge, the older it is.

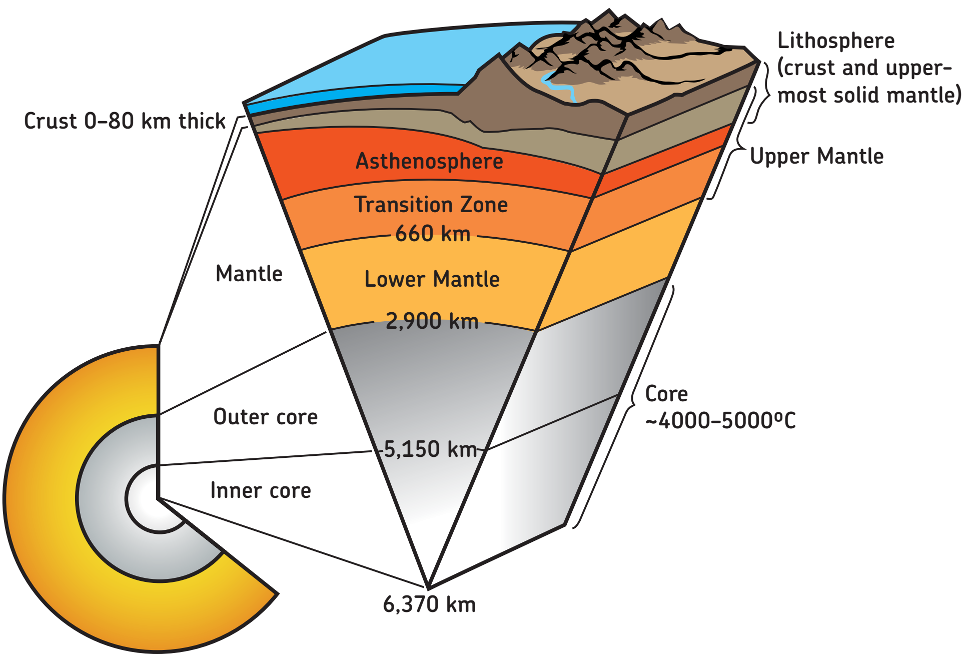
Scientists observe the record of geomagnetic field reversals on the ocean floor. Minerals in the "stripes" of new crust formed by seafloor spreading record the prevailing geomagnetic field direction at the time of their formation. The stripes on one side of the oceanic ridge are a mirror image of those on the other side. The magnetic variation in successive bands of ocean floor that run parallel to oceanic ridges is important evidence supporting the theory of plate tectonics.

JOURNEY TO THE CENTER OF THE EARTH

The *crust* is the familiar, rocky outer shell of the planet Earth. Under the oceans, it is typically 5 to 10 km (3 to 6 miles) thick and made up mostly of dense rock, which is rich in magnesium and iron. Continental crust is thicker, typically 30 to 45 km (18 to 28 miles) thick, but is made up of less dense rock, rich in silicon and aluminum. But what's beneath this? Let's take a look.

Beneath the crust lies the *mantle*, a rocky layer that makes up most of Earth's volume (about 84 percent). The mantle can be divided further into the *upper mantle* and *lower mantle*.

Within the upper mantle, there are several layers with different degrees of rigidity. At the very top is a solid layer of rock, which—along with the crust—forms the *lithosphere*. Below that is the *asthenosphere*, which is hotter and less rigid than the lithosphere. This second layer flows very slowly, causing the tectonic plates above it to move. Between the asthenosphere and the lower mantle is the *transition zone*. It is here that high pressures and high temperatures cause several key phase transitions to occur that transform *olivine*, the most abundant mineral in the upper mantle, into *bridgmanite* (magnesium silicate perovskite)—the most abundant mineral on Earth—and *ferropericlase*.

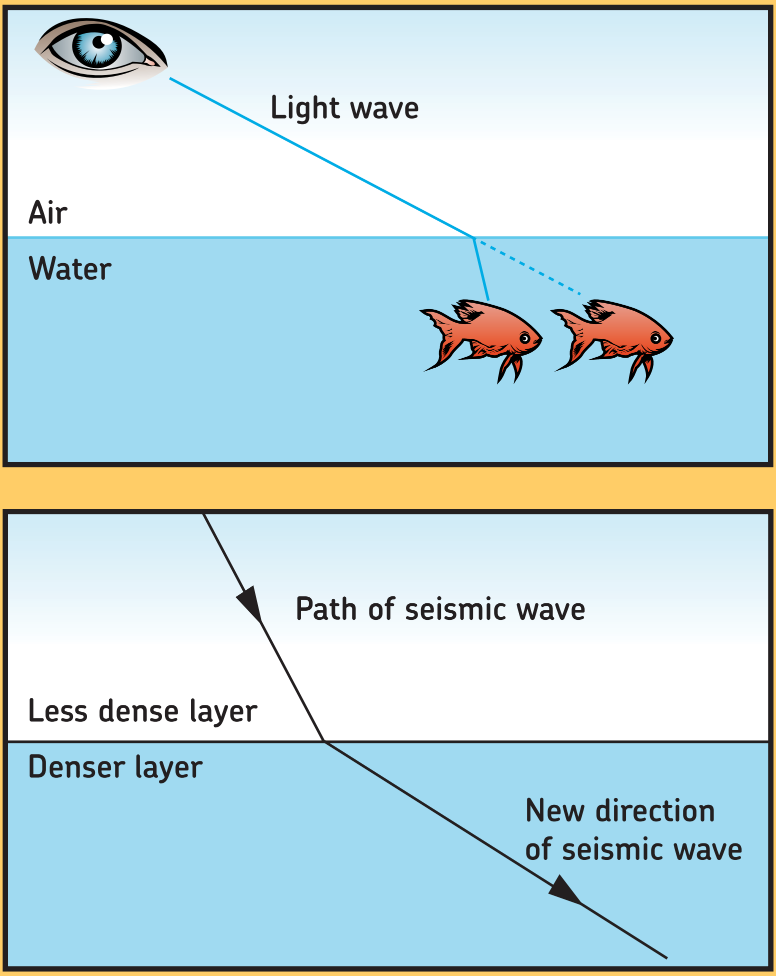


Simplified cross-section to scale

Detailed cross-section not to scale

Traveling even deeper, we find Earth's *core*, which is the innermost part of our planet and made primarily of an iron-nickel alloy. The boundary between Earth's mantle and core lies around 2900 km (1800 miles) beneath the Earth's surface.

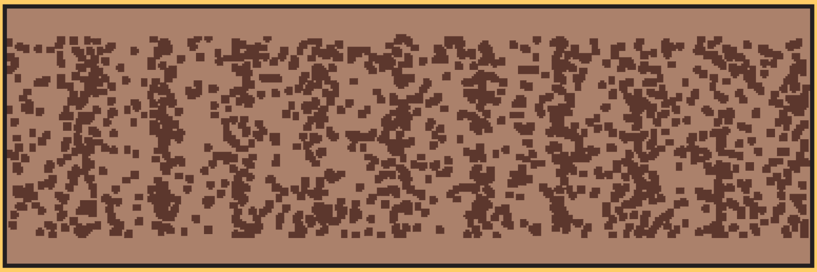
How can scientists tell that there's a difference in material if they haven't actually been there? They measure how fast *seismic waves* travel through the Earth. In the same way that light, which behaves like a wave, is refracted (bent) as it moves from air to water, seismic waves experience similar changes in direction and speed as they move from crust to mantle to core and back, and scientists can observe these changes.



Ever notice how light waves bend as they travel between air and water? In the same way, a seismic wave is refracted as it moves through different mediums in Earth's interior!

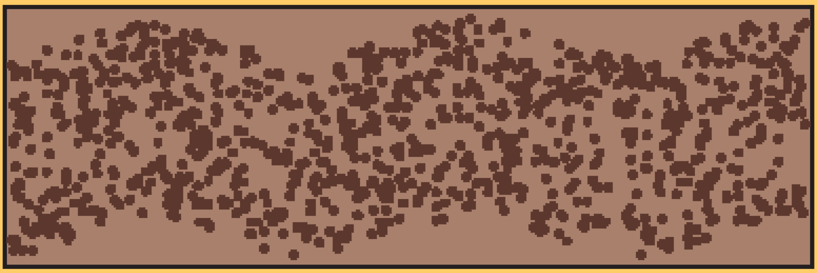
There are many different kinds of seismic waves, but we'll focus on two in particular that travel throughout the Earth. Because they primarily move inside the Earth, and not on its surface, we call them *body waves*. The first are *P-waves* (primary waves), which travel through a material by alternately compressing and stretching it.

P-waves are the fastest waves to emerge from an earthquake or seismic event. You can imagine them moving through the Earth with a motion similar to a Slinky!



P-waves are like a Slinky—a compression or longitudinal wave. Darker regions show where the material is more compressed.

S-waves (secondary or shear waves), on the other hand, move in a direction that is perpendicular to that of wave propagation (the direction the wave travels). S-waves are like waves in a flag, or the wave a guitar string makes when you pluck it.



S-waves move like waves in a flag. Scientists call this kind of wave a *transverse wave* because its motion is perpendicular (transverse) to wave propagation.

S-waves involve a change in *shape*, while P-waves involve a change in *volume*. Because liquid cannot be sheared into a new shape, S-waves can't travel through liquid, but P-waves can.

By observing the differing nature of these waves, scientists have been able to deduce that the outer core is liquid. P-waves travel right through the outer core, while S-waves don't. The *inner core* is solid and begins about 5150 km (3200 miles) beneath the Earth's surface. This innermost, hottest portion of the Earth is about 1220 km (760 miles) in radius, and both P- and S-waves travel through it.

The temperature of the Earth's core is difficult to determine because there's really no thermometer long enough to reach it or strong enough to withstand such high heat and crushing pressures. Instead, scientists infer its temperature through the use of sophisticated experiments and computations. Estimates for the core range from about 4,000°C to 5,000°C. The hottest part of the inner core is about the same temperature as the surface of the Sun (which is the star's coldest part).

EARTHQUAKES, VOLCANOES, AND TSUNAMIS!

The boundaries of tectonic plates are responsible for much more than just ocean trenches and oceanic ridges. They're also the cause of the most dramatic changes in Earth's landscape, including *earthquakes*, *volcanoes*, and *tsunamis*.

As a result of pressure, friction, and plate material melting in the mantle, earthquakes and volcanoes are common near convergent boundaries. In these areas, you'll also find *faults*, which are *planar fractures* (or cracks) in the rocky crust where significant movement of the rock occurs along the fracture. Most earthquakes are caused by the rapid movement of plates on active faults at plate boundaries.

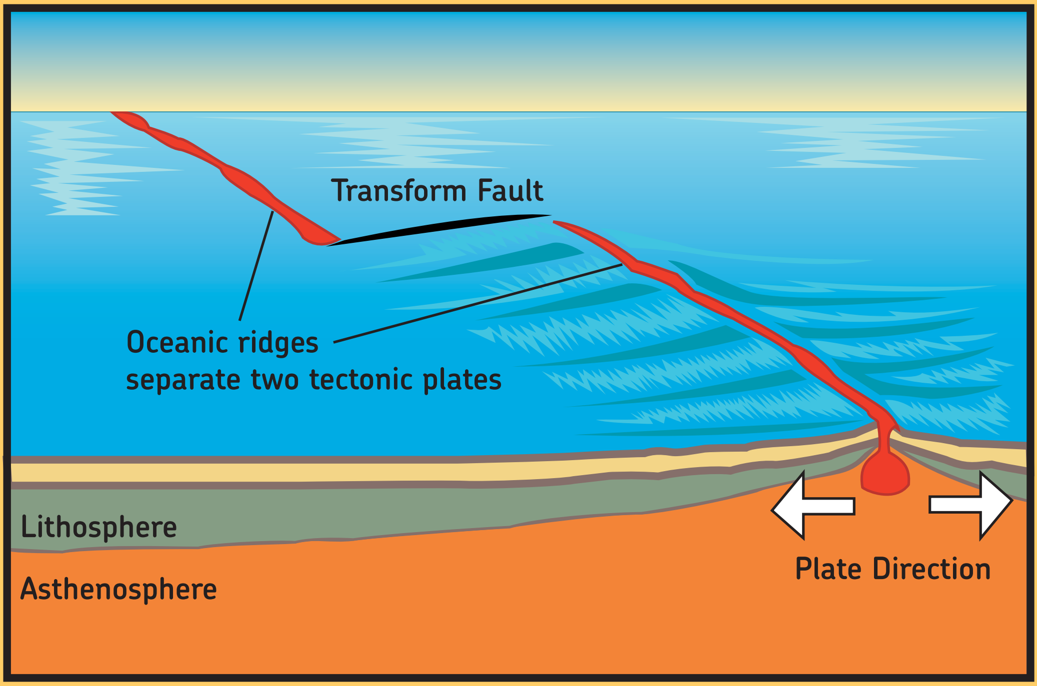
Because earthquakes can be so destructive, scientists make a special effort to study them. The sudden release of energy during an earthquake sends seismic waves traveling through the Earth. Earthquakes are measured using *seismometers*, instruments that have the ability to measure ground motion generated by distant earthquakes and volcanic eruptions, as well as other activity, such as explosions. Records of seismic waves allow seismologists to map the interior of the Earth, as well as locate earthquakes and measure their size.

Earthquakes can happen close to the Earth's surface or deep beneath it. All else being equal, the shallower an earthquake, the more damage it causes to human structures.

The *epicenter* of an earthquake is the location on the *surface* of the Earth directly above the point where the earthquake originates or where the fault begins to rupture. Usually, the epicenter is also the area where the greatest damage occurs. The place *within* the Earth where the earthquake actually originates is called the *focus*.

One fault familiar to many Americans is the San Andreas Fault, which runs through California. This is an example of a nearly vertical fault, where the rock on either side moves horizontally with very little vertical motion. It is called a *strike-slip fault*. Plate boundaries with this type of motion are also called *transform boundaries*.

Yet another name for them is *conservative boundaries* because no land is formed or consumed where the two plates meet. These faults, which are found all over the Earth, end abruptly by connecting to other faults, ridges, or subduction zones. Most transform faults are hidden from view on the ocean floor, where they form a series of short zigzags accommodating seafloor spreading. These transform faults relieve strain caused by stress in the rock due to the spreading ridges. But the best known (and most destructive) are those on land at the margins of tectonic plates.



The aftereffects of an earthquake often cause more damage than the earthquake itself. In the case of the 1906 San Francisco earthquake, most of the damage to the city came from fires that started because the earthquake ruptured gas lines. The city survived the earthquake but was gutted by the fires that followed.

We measure the intensity of an earthquake using the *moment magnitude scale*, which ranges from 0 to nearly 10. With each 1-unit increase on the moment magnitude scale, the energy released by an earthquake increases about 32 times. That means an earthquake of magnitude 8 is about a thousand times stronger than one that's magnitude 6. Every year, the Earth has more than a *million* light or moderate earthquakes that register below 6 on the moment magnitude scale.

The fire after the 1906 San Francisco earthquake took four days to burn itself out and caused massive destruction.

A *tsunami* is a series of huge, destructive waves in an ocean or large lake that is triggered by an earthquake or another major disturbance (like a landslide or a meteor impact—anything that displaces a lot of water very suddenly). The wavelength of a typical tsunami can be huge, reaching up to 200 km (120 miles) from one wave crest to the next. Out in the middle of the ocean, these enormous waves are so spread out that they might not look out of the ordinary, but once they reach shallow water near a shore, they rapidly become compressed, and their amplitude (height) spikes. In extreme cases, tsunami waves can grow to heights of more than 30 meters (almost 100 feet) as they reach the shore!

The immense amount of water that a tsunami is capable of moving makes these events particularly destructive. Because of this danger, many areas that are vulnerable to tsunamis have warning systems in place to alert their citizens to move away from the water and find higher ground. These systems, when in place, can greatly minimize loss of life. Japan, due to its position above a subduction zone, has built sophisticated early earthquake and tsunami warning systems. While these alerts might not lessen damage or loss of life near the epicenter, they can warn those farther away. Because tsunamis can travel so far—across oceans—to spots very distant from where they were first generated by an earthquake, warning systems are sometimes able to give many hours' notice of an impending tsunami.

A *volcano* is an opening in the Earth's crust that allows hot magma, volcanic ash, and gases to escape from below the surface. Volcanoes can drastically reshape the land, though they're not always as dramatic as shown in movies and on TV. Some volcanoes work extremely slowly, without big explosions.

Lava is the name of both the molten rock erupted by a volcano and the rock that has solidified and cooled. Inside the Earth, this same material is called *magma*. Besides containing molten rock, magma may also be composed of suspended crystals, dissolved gas, and sometimes gas bubbles. Magma often collects in magma chambers, which may feed a volcano or cool and turn into a *pluton*, a body of crystallized rock. Magma can intrude into adjacent rocks, extrude onto the surface as lava, and explode into the air as *ejecta*. Rocks that are formed from the cooling and solidification of lava or magma are called *igneous* rocks. Two very common types of igneous rocks are basalt and granite.

Volcanoes are commonly found at both divergent and convergent boundaries. Volcanism away from plate boundaries also occurs; this activity is due to *hotspots*. Well-known examples include Hawai'i and Yellowstone. Hotspots are thought to be thermal upwellings of abnormally hot rock that start deep and rise through the Earth's mantle before erupting at the surface. Volcanoes can also form a chain of islands situated above a subducting plate; this is called a *volcanic island arc*.

The *Ring of Fire* is an area surrounding the Pacific Ocean where a large number of earthquakes and volcanic eruptions occur. A horseshoe shape about 40,000 km (25,000 miles) long, this area is associated with a nearly continuous series of trenches, island arcs, and volcanism. The Ring of Fire is home to more than 75 percent of the world's active and dormant volcanoes.

The 1980 eruption of Mount St. Helens is a dramatic example of volcanic activity. In this photo, ash and smoke billow from the mountain's smoldering top.

Credit: U.S. Geological Survey

WHAT DO GEOLOGISTS DO?

Are there really adults who get paid to look at rocks all day? And what is it that *geologists* actually do? Geologists can take a number of different career paths.

You've already heard about the geologists who study earthquakes (*seismologists*) and volcanoes (*volcanologists*). These scientists try to find new ways to understand earthquakes and volcanic eruptions in order to protect human populations near active volcanoes or faults. They assess risks and make recommendations to people who live in hazardous areas.

There are also geologists who study the Earth to figure out its ancient history. Our planet's past is a hugely fascinating mystery. Some geologists are drawn not only to this prehistoric drama but also to more recent history, like changes in Earth's magnetic field, atmosphere, and climate. While there is no "written" history of how the Earth formed and has evolved over its more than 4.5 billion years, the rocks hold many clues to past events, climates, and organisms. By investigating ancient rocks, research geologists can sometimes find the keys to modern issues.

There are also other scientists, like me, your author Dr. Lee, called *geophysicists*. I conduct experiments trying to reproduce the extreme conditions of the Earth's interior to see how rocks behave, change, and deform under high pressures and temperatures. Other geophysicists run convection models to investigate how the Earth cools itself and how tectonic plates have moved over time.

Some geologists seek out the Earth's natural resources. They work for mining or energy companies, locating and extracting the materials we use in our everyday lives. The aluminum in your soda pop can was originally aluminum ore found by a geologist. When you drive in a car, its motion is powered by gasoline, which is extracted from oil that forms deep underground.

Some geologists work to prevent environmental damage—for example, during construction or logging of forests. Others focus on changes in Earth's atmosphere and oceans and on preventing environmental damage due to climate change.

And yet another subset uses their knowledge of the Earth to draw inferences about other planets within our solar system and beyond.

GEOLOGY ACTIVITIES!

Wondering how to put your newfound knowledge of geology into practice? Check out these websites. For a clickable list of the following links, visit *http://www.nostarch.com/tectonicscomic*.

SCHOOLYARD GEOLOGY!

Geology is everywhere around you—you might be surprised at what you can find out if you take a closer look at the rocks in your day-to-day environment! Here are some activities to try in your schoolyard.

➔ ***http://education.usgs.gov/lessons/schoolyard/***

LEARN HOW ENGINEERS BRACE BUILDINGS IN CASE OF EARTHQUAKES!

In this delicious classroom exercise, you'll construct a building (made of toothpicks and marshmallows) to withstand an earthquake. You can even use Jell-O to simulate the shaking of the earthquake!

➔ ***http://www.teachengineering.org/view_activity.php?url=collection/cub_/activities/cub_natdis/cub_natdis_lesson03_activity1.xml***

CREATE YOUR OWN TSUNAMI!

Wonder how those giant waves actually form out at sea? Make a mini-tsunami all of your own.

➔ ***http://mceer.buffalo.edu/infoservice/Education/makeTsunamiDirections.asp***

A VOLCANO CRISIS SIMULATOR!

In this simulation, your job is to become a volcanologist—to collect and interpret data that might hint at volcanic activity. Will there be an eruption in the near future?

➔ ***http://www.dartmouth.edu/~renshaw/eruption/***

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UPDATES

Visit ***http://www.nostarch.com/tectonicscomic*** **for updates, errata, and other information.**

AN AMAZING, EARTH-SHATTERING ADVENTURE!

The Incredible Plate Tectonics Comic is a wild adventure in earth science. Follow Geo and his robot dog, Rocky, as they travel back in time to Pangea, surf a tsunami, and escape an erupting volcano—all in time for Geo's first-period science test!

The journey starts 200 million years ago and takes you to modern-day Hawai'i, the ocean floor, and deep inside the Earth.

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* Why the Earth shakes
* What's in the center of the Earth
* How volcanoes can form islands

The Incredible Plate Tectonics Comic will teach you about geology in a fun, lively, and visual way.

About the Authors

Dr. Kanani K.M. Lee is an associate professor in the Department of Geology & Geophysics at Yale University. Adam Wallenta is an illustrator, colorist, and writer who has worked for companies such as Marvel Comics, DC Entertainment, and more. They live near New Haven, Connecticut, with their son.

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