

Scientific Background for *Upward and Outward: Scientific Inquiry on the Tibetan Plateau*

This article summarizes the science behind the research project featured in the educational documentary film, *Upward and Outward: Scientific Inquiry on the Tibetan Plateau*. The 20-minute film portrays the process of scientific inquiry in a multi-disciplinary research study. The film describes the process of science as seen in a real-world example of how scientists pose questions, plan and carry out investigations, and interact with each other. Because the point of the film is not to explain particular scientific concepts or discoveries, the film's message is not specific to Earth science—it can be used by science teachers in any field.

Nonetheless, some viewers may be curious about the scientific topics referenced in the film. Some teachers may feel more comfortable if they can help to answer student questions. Thus this article provides supplementary, non-essential background about the scientific underpinnings of the project. Because the film highlights different types of evidence, this article focuses on how the scientists gather and interpret this evidence. Techniques are treated as “black boxes”, emphasizing the concepts behind them and the conclusions that can be drawn. While the scientific content of the research is indeed fascinating, we encourage teachers to present the film as an inside glimpse of science at work, and to focus students' attention on that process.

The Tibetan Plateau and its Tectonic Origins

Across the varied terrain of Earth's rivers, mountains, plains and hills, the Tibetan Plateau is the largest single land feature on our planet. Stretching 3500 km long and 1500 km wide, across the boundaries of several countries, this land region includes the highest peaks on Earth—the rugged ranges of the Himalaya and Hindu Kush of India, Pakistan, Tibet, Nepal, and southern China. These mountains rim the edge of a high plateau that averages 5000 m in elevation—a region a third as large as the contiguous United States and taller than the highest peaks of the Rocky Mountains. This extended high region is called the Tibetan Plateau.

The Tibetan Plateau is not only the largest, highest area in the world today—it may be the largest and highest in all of geologic history. The set of events that formed it, and continue to build it, appears to be unique. This region was formed through the action of plate tectonics, the movement of the plates that compose Earth's crust. Driven by heat deep inside the planet, the plates move around the Earth, separating in some places and colliding in others. Where plates meet, new mountain ranges and deep ocean trenches are built. Plate boundaries are also good locations to study plate tectonics—how and why the plates move, and how their movements form Earth's varied landscapes. The Moon, and most other bodies in our solar system, do not have active plate tectonics, and thus do not have the topographic variety that we see on Earth.

The Tibetan Plateau began construction over 100 million years ago, when India was a separate continent, like Australia today. The Indian plate was moving northward at a rate of nearly 15 cm per year—this sounds slow, but it is high speed for a whole continent! About 50 million years ago, the Indian plate began to collide with the Eurasian plate. This massive collision compressed Earth's crust and crumpled up a broad area into mountains and high plains, the Tibetan Plateau. As the crust compressed, heating from the collision raised the mountains even higher.

Why does the plateau interest geoscientists?

Today, the Tibetan Plateau is rich in geologic evidence of this collision, both past and ongoing. At its southern edge, where the collision was most direct, geologists can identify the jumble of rocks as originating from two separate plates. From the size of the deformed region, they can determine that the Indian plate has so far pushed more than 2000 km into Asia. They can

measure the increased thickness of the crust in this region—nearly double the average crust thickness, as the crust is compressed and compacted with nowhere else to go. By dating the rocks and using computers to model plate movement over time, they have found that the collision began about 50 million years ago.

Geologists can measure the continuing motion of the plates today. Although the collision has slowed the Indian plate, this plate still pushes northward into Eurasia. Earthquakes occur frequently along the southern edge of the plateau, where rocks slip along faults, or breakage lines. And the high mountains are getting higher: Satellite measurements of the Himalayan peaks show that they are still rising at about 3 mm per year, and even faster in some areas.

Scientists also find evidence of the plate collision in the erosion history of the plateau. As the plateau grows upward, erosion cuts it down. Steep topography means that water runs downhill quickly, eroding the rock and carrying away silt and sediment. On the south side of the plateau, the plateau receives high rainfall from the Indian monsoons. This high rainfall creates some of Earth's largest rivers—the Indus, Ganges, and Brahmaputra systems—which carry enormous loads of sediments away from the mountains to form huge river deltas.

Higher in the plateau, erosion has formed deep valleys, cut by fast-moving mountain rivers. These rivers deposit sediments in the valleys and basins between the mountains, which accumulate to enormous depth over many years. Over millions of years, these sediments may be turned to rock. Thus geologists can see evidence of today's erosion processes in the river canyon. Evidence of past erosion is preserved in the sedimentary rock deposited by long-ago rivers. This erosion history too provides clues to the uplift that caused it.

Scientists are also interested in how the plateau interacts with the atmosphere. Mountaineers on Everest speak of how this peak “creates its own weather” as it interferes with the jet stream. As an enormous wedge of land jutting into the sky, the Tibetan plateau affects weather in the entire region by altering the movement of air masses. Monsoon winds from the Indian ocean dump rain on the plateau's south side but are blocked from going further north. So the south side of the plateau is wet, but the north side of the plateau is arid, receiving just a few cm of rain per year. In the north, winds steered by the plateau cause giant dust storms in China.

Research questions

These phenomena show that the Tibetan Plateau is an interesting and influential part of Earth's system. In this film, we follow a group of scientists who have come together to study this enormous landscape feature. They are interested in understanding in detail how the Tibetan Plateau was built. As the Indian plate plowed into Asia, was the plateau pushed up all at once, rising as one enormous feature—or did it gradually grow outward as the collision proceeded?

The answer to this geologic question also has consequences for the region's climate. The scientists want to understand how the climate in this region changed as the plateau grew upward and outward. Understanding how and when the plateau was built by plate tectonics will shape their search for evidence of climate change and the explanations they develop. The scientists suspect that these geologic and climate changes are closely related—but did these changes all occur at the same time, or separately? Are they related, and if so how?

An Earth systems approach

The scientists have some previous evidence for their suspicion that the climate of the plateau is connected to its geology. They also use logic to consider how mountains relate to weather in

general. Monsoon rains erode the uplifted region, but as the region is uplifted, it interferes with atmospheric circulation and alters the effects of the monsoon. Rain may fall in different areas, increasing erosion in some places and decreasing it elsewhere. And, as the mountains are eroded away, the Earth's crust becomes lighter, thus increasing its buoyancy and increasing the amount of uplift. This feedback between rainfall, uplift, and erosion means the scientists must take a "systems" approach to these questions. They cannot examine only the tectonic processes, or only the changes in weather and climate patterns—they must consider tectonic and climate processes as related to each other, involving the entire Earth system, not just its separate parts.

Because they are taking a systems approach to the research, the group also requires expertise in a wide range of scientific specialties. They need geologists who can decipher the faults and folds in rock that give evidence of uplift processes, and others who can understand the history of past erosion as seen in sedimentary rocks. They need geophysicists who can interpret seismic and gravitational data about the deep Earth processes that cause these surface changes.

Paleontologists will interpret the fossil record and provide dates for the geologic changes that have occurred over time. A specialist in paleoclimate, or ancient climate, will find and interpret evidence about what the climate was in the past, and a meteorologist will use computer models to explain how the movement of air masses would change as the plateau grew outward and upward. The group will use many different techniques and draw on many different sources of background knowledge—no one person could be expert in all these areas. Using a team approach, they will connect and make sense of all the different kinds of evidence.

The edge of the plateau: Seeking evidence for change

This group is studying the northern edge of the Tibetan Plateau. Although this edge is far from the original zone of plate collision, the plate collision has also caused this area to rise. The rocks of Asia are being pushed aside, just as snow is pushed aside by the accumulating snow at the front edge of a shovel. The scientists will look for evidence for how the uplift has occurred, and whether it took place suddenly or gradually. This in return will give them clues about the tectonic processes deep in the Earth's crust that caused this uplift.

This northern region also provides important clues to specific atmospheric changes caused by the plateau uplift. Today, the high plateau blocks monsoon winds and moisture from the south, and the north is dry. The northern climate is influenced mainly by dry air from central Asia, rather than moist air from the Indian and Pacific oceans. But back when the plateau was lower and smaller, more moist air may have reached the region, providing a wetter climate. Evidence from river basin sediments deposited millions of years ago will yield information about erosion processes and rainfall patterns of the past. These paleoclimate clues help the scientists to decipher when and whether the climate has changed over time. Together, the scientists will gather many kinds of data, interpret the evidence, and combine it to build a single, collective story about the geologic and climate changes of the Tibetan plateau.

Researchers at Work: Gathering and Interpreting Evidence

This section briefly outlines the scientific approaches and types of evidence that will be gathered, and how each type of evidence is expected to contribute to the overall story. These types of evidence are not described in detail in the film; understanding them is not the learning goal. This information is provided as enrichment for teachers and as background for those who may enjoy understanding the back story of the film.

Evidence from geologic structures: Faulting and folding

In the field, scientists look for structural features that offer evidence about mountain-building processes. Pressure from tectonic action deep underground stresses and breaks rock layers. Geologists can spot these broken spots, or faults, by looking for places where the rock layers do not match up, but are offset or shifted from where they originally formed. Scientists can locate where rock stress has been highest and can measure what direction and how far various sections of crust have moved. This type of evidence is gathered by field work—locating and measuring rock types, mapping them, and marking the faults.

Evidence also comes from sedimentary rocks. Because sedimentary rocks are deposited in flat layers, any folding or bending of layers shows that they have been distorted by tectonic forces. Because the youngest sedimentary layers are on top, and the oldest on the bottom, the timing of distortion can be determined from which layers, upper or lower, are bent, and which are not. Dating the rocks, using fossils or chemical techniques, gives more detailed evidence about when the bending or folding occurred. This type of evidence also comes from field work, examining the sedimentary rock layers, mapping their folds, and collecting samples for dating.

Evidence from igneous rocks: Temperature history and uplift

In areas of high elevation, erosion proceeds rapidly—rainwater runs downhill, gathering energy to erode the rock and carry away sediments. Rocks that were once buried deeply, become closer and closer to the surface, as the overlying layers erode away.

The depth of underground rocks below Earth's surface relates to their temperature: rocks deep underground are hotter, and rocks near the surface are cooler. Rocks have a kind of internal thermometer that can reveal how long they have been near the surface. This thermometer depends on the natural process of radioactive decay of certain elements in the rock. The mineral apatite, found in granites and other igneous rocks, contains atoms of uranium and thorium. These atoms decay and give off an alpha particle, or helium atom. Helium is a gas, so if the rock is warm, the helium atoms will be able to escape, just as helium in a party balloon escapes through the walls to deflate the balloon. But if the rock is cool, its minerals are too rigid for the helium to escape, and the helium is trapped. That is, helium is trapped inside the apatite when the rock is cool, and helium escapes when the rock is warm.

Since rocks cool as they get closer to the surface, the deepest, warmest rocks do not trap any helium. But cool rocks nearer Earth's surface (less than 2 km deep) do trap helium. The longer these rocks have been shallow and cool, the more helium they will have trapped over time. So geologists collect rock samples and analyze the amount of helium trapped in the apatite minerals. Some samples will come from rocks that were uplifted and excavated long ago; these areas have been at shallow depths for millions of years and will have trapped a lot of helium. However, other rocks were only recently eroded; they have been deep underground until very recently. Because they have been warm, this type of rock will not have accumulated much helium yet.

In order to gather this type of evidence, the scientists collect rock samples from different areas along the northern edge of the plateau. Layers are exposed along river canyon walls, where erosion may have been recent or long ago. They return the samples to the lab, crush them, separate the apatite minerals, and measure the amount of trapped helium. From these measurements, they can determine how many years ago each sample reached the shallow depths near Earth's surface: Was it uplifted and exposed by erosion recently or long ago? By comparing

samples from different parts of the plateau, scientists can compare the timing of uplift at each site. If all the sites were exposed at about the same time, the scientists would conclude that the plateau rose suddenly. If they observe a gradual progression of exposure times, the scientists would conclude that the plateau rose more gradually, with some portions raised before others.

Evidence from sedimentary rocks: Erosion history and age dating

Another type of evidence comes from sedimentary rocks deposited in mountain valleys and basins. The grain size of particles in sedimentary rock provides evidence about the environment in which sediments were deposited: fast-moving water deposits large cobbles and pebbles, while slow-moving water deposits smaller sands. Calm lake waters deposit very fine-grained silts. Thus the grains in sedimentary rock—large, medium, or small—tell where the sediments were deposited, in a mountain stream or a quiet lake. In periods when uplift is occurring rapidly, erosion will also be rapid—mountain streams will be common—but when uplift is less rapid, erosion will be slower, and meandering rivers or quiet lakes can form. Durable minerals in these sediments, such as zircons, can be matched to the rock of the nearby mountain ranges. The scientists can thus determine the original source rock for the sediments: from which nearby mountain ranges did these basin sediments erode?

Sediments deposited in lakebeds also record Earth's magnetic orientation at the time they were laid down. Magnetic minerals in the sediments will be oriented, or pointed along the direction of the Earth's magnetic field. When the north and south poles flip, as they have done often in Earth's history, the layers of sediments laid down after the flip will magnetically point in the opposite direction. Thus the sequence of magnetic orientations in the sediment layers in an ancient lakebed will match the sequence of pole flips, alternating with the magnetic direction of Earth's poles at the time the sediments were laid down. When the sediments harden to rock, that magnetic sequence is preserved. The history of pole flips is well-known, so it can be matched up with the sequence for any section of lakebed sediments to identify when those sediments were laid down. Thus, the sediments can be dated and linked with periods of rapid uplift and erosion.

Evidence from sedimentary rocks: Paleoclimate

Sedimentary rocks provide evidence about the rainfall that fell on this region in the past. Rain is just water, with the chemical formula H_2O , but the oxygen atoms in water can be of different isotopes—O-16 or O-18, where O-18 is a slightly heavier version of the oxygen atom (with 2 more neutrons). Although these heavier or lighter water molecules behave nearly identically—you could drink both types safely—atmospheric processes such as evaporation and precipitation will tend to slightly separate these types of water molecules over time. Regional differences in the rates of these processes cause some air to carry water that is enriched in O-18 (more heavy water), and some to carry water that is depleted of O-18, or have less heavy water.

Paleoclimate scientists can identify the type of rainfall that fell on ancient sediments by analyzing the carbonate minerals in the sediments. When carbonate minerals are deposited from soil, river, or lake waters, the carbonates will have more or less oxygen-18 depending on the oxygen in the waters that deposited them. Like an ancient rain gauge, the minerals in the sedimentary rocks provide evidence of the type of rainfall that made up surface water long ago. Thus measuring the amount of O-18 in these carbonate minerals provides information about the source of ancient air masses that carried the precipitation that fell long ago.

To gather this type of evidence, scientists collect samples of sedimentary rocks that contain carbonate minerals from ancient soils, lake and river deposits at different sites across the northern edge of the plateau. Back in the lab, they crush the rock and measure the amount of O-18 in each sample. By comparing their samples to other rocks with known rainfall sources, they can determine if the proportion of O-18 in the carbonate is greater than normal—enriched—or less than normal—depleted.

This lets them make deductions about the climate at the time the rocks formed. Central Asian air tends to be both dry and enriched in oxygen-18, while air coming from the Indian and Pacific oceans is both wetter and depleted of oxygen-18. Thus, on the Tibetan plateau, samples that are enriched in O-18 must have experienced weather that was most influenced by central Asian air, and thus deposited in arid periods. Samples that are depleted in O-18 experienced rainfall influenced by Indian and Pacific ocean air, and thus these sediments were laid down during a wetter period. By comparing samples from different sites, scientists can identify if and when a climate change from wetter to drier took place. By matching the timing of wet or dry climates with the magnetic dates, they can identify when a change occurred. And by comparing to the geologic evidence, they can determine whether uplift and climate change occurred at the same time—thus suggesting that uplift caused the climate change—or whether they were separate events. They can determine whether climate change occurred suddenly or gradually.

Evidence from geophysics: Tectonic processes

Geophysicists use physical measurements to determine properties of rocks too far underground to observe directly. For example, seismic waves traveling through the lower crust and mantle change speed when they encounter a different rock type. When an earthquake occurs, seismometers detect the waves sent through the Earth by the quake. By recording the speed at which these waves travel, scientists can deduce some of the properties of the underlying rocks, such as their density and chemical composition. Chinese scientists have already gathered much of this evidence, so this is an important contribution that they will make to the project. Gravity measurements are also used to determine the “shape” or distribution of deep rocks. Tiny variations in the gravitational force at the surface mark density differences in the rocks below.

The scientists will be using geophysical data to understand some of the properties of the deep crust and upper mantle under the plateau, and thus to gain clues about the tectonic processes that take place below the plateau. For example, are the deep crust and mantle rocks folded, like the surface rocks that are also buckled into mountains? As the crust compresses and heats, do these rocks eventually heat up and flow away, or drop off in a blob?

Evidence from computer modeling: Past and present atmospheric circulation

The scientists are trying to connect the geologic evidence about the uplift of the plateau with the evidence of changing climates to see if they are related. They can't go back in time to directly measure what the climate was like 10 or 20 million years ago—but they can gather paleoclimate evidence from the rocks. They can also run computer models to predict the circulation of the atmosphere in different situations. First they test the model to make sure it correctly predicts today's climate. Then they run imaginary models that resemble the situation of the plateau in the past, when it was smaller. If the computer model predicts a climate that changes as the plateau grows, and if that prediction is similar to what the paleoclimate evidence reveals, the scientists will feel more confident that they have interpreted the paleoclimate evidence correctly.