Ride the Rock Cycle:
Will you become a mine?

Notes for Teachers

The rock cycle is used to help students understand the dynamic nature of the rock and mineral materials that make up the crust and mantle of the Earth. The natural processes that take place on, below, and above the surface of the Earth move materials through a variety of cycles: water, nitrogen, carbon, and rock. This activity is designed to teach your students about the rock cycle and the processes that move rocks through this cycle. By moving around the room from station to station, they will learn that the rock cycle is not linear and that all rocks don't follow the same paths. They will also come to understand that the rocks and minerals that we mine for items we use in our daily lives did not form everywhere; they formed in particular environments at particular times in the geological past.

This activity is similar to "ride the rock cycle" activities that you may have used in the past. It is different in that it adds time to the movement from one station to another. Because the students are moving through the rock cycle in geologic time, the numbers are large numbers of years. The setup should make it easy for students to do this even without a calculator. Having time added to the activity permits the students to construct a geologic history of the travels the atoms in the rocks make through the rock cycle.

Time to complete: two class periods or possibly one, if on a block schedule. It is good to plan for two days as that will provide time for the teams to share their results and have some discussion about the nature of economic accumulations of rocks and minerals (ores). Which type of ore was formed most frequently? How many teams did not have the right age and type of rock to form one of the ore deposits? Were deposits created then destroyed by subsequent processes that changed them into another type of rock?

Prerequisites: It is helpful if the students have had prior instruction in the different rock types and how they are formed. A one-page diagram helps to explain the processes involved in the rock cycle. In this activity, the classic three rock types (igneous, metamorphic, and sedimentary) are subdivided into volcanic (extrusive igneous), intrusive igneous, metamorphic, clastic sedimentary, and chemical sedimentary rocks. An understanding of plate tectonics is also helpful.

Materials:

- 12 Station labels (copied onto card stock or laminated for repeated use)
- 12 copies of the one-page diagram of the rock cycle (copied onto card stock or laminated)
- Rock-cycle data sheets (one for each two-person team of students)
- Geologic history sheet (one for each two-person team of students)
- Pairs of six-sided dice (one pair for each two-person team of students)
- Optional samples of rocks and ores.

Possible answers to some of the questions:

1. Where did you spend the most time? Answers vary depending on the data.

2. Why do scientists call the rock cycle a cycle? Cycles are series of events that repeat themselves, not always in the same order and not always in the same sequence, as in the case of the rock cycle. In the rock cycle there are natural processes that move the rock material through changes from one rock type to another. The rock cycle is considerably slower than other cycles on earth: for example the water cycle is much faster.

3. Where do weathering and erosion occur? Near or on the earth's surface.

4. List the processes that move the rocks through the rock cycle. Compaction and cementation, high temperature and pressure, melting, cooling and crystallizing, weathering and erosion, dissolution and precipitation.

5. Explain the forces or sources of energy that create these processes. They are the forces of nature: wind, water, gravity, temperature and temperature changes, light, magnetism. These forces move materials through the rock cycle. The Sun provides most of the energy for surface processes. Radioactive decay, and, to a lesser extent, internal heat from the formation of the Earth, drive most of the other processes.

6. If you were at the Earth's surface, what type of rock were you when you got there? Answers vary depending on their data.

7. Look at your data. Pay attention to where you are located geographically (either Alaska, Hawaii, or the western, central, or eastern conterminous United States. Could you have formed any of the above ore deposits? If so, which ones? Answers vary depending on the data. For Example 1, no; the volcanic rock is too young to have ore deposits; the metamorphic rock is also too young for crushed stone (gneiss) and too old for Carlin-type gold deposits; and the intrusive igneous rock is too old for porphyry copper or molybdenum deposits and too young for platinum or rare earth elements. For Example 2, yes; the chemical sedimentary rock (youngest rock) could have gypsum in the western U.S. or phosphate deposits in the eastern U.S. The middle, clastic sedimentary rock could have had coal or uranium, and the oldest sedimentary rock could have had a number of deposits (limestone, barite, gypsum, potash, salt, coal, uranium, lead or zinc), but these middle and oldest rocks were later eroded. Also note, that actually having an ore deposit of a particular type depends on where you are (e.g., eastern, central, or western U.S.) as well as the appropriate age of rock.

8. Assuming that you did form an ore deposit, was the deposit preserved and located near the surface so that it can now be mined? Or was the deposit weathered and eroded away in the years after it formed? Answers vary, depending on data, but the only deposits that can be mined are the ones contained in the youngest rock, as that one still exists.

9. Take a survey of your class and list the number and types of deposits formed through this activity by everyone in the class.

10. Did this exercise help you understand how infrequently economic accumulations of rocks and minerals occur on earth? Explain: Generally not many rocks actually end up being an economic deposit. Rocks and minerals are where they are because of the forces of nature; we can't put them

where we would like them to be. Therefore, we must mine them in place, which can be controversial. We have choices over where to build a city or a road or a farm field, we do not have choices when it comes to the locations of natural resources from the crust. We can't mine it where it doesn't exist. And if we don't mine, how do we live? Our lives depend on mining for food, housing, clothing, transportation, communication, lighting, heating/cooling, health and safety. Consider the average life span in the Stone Age (when they mined stones for tools): 25 years. Now consider the average life span in the United States today: 85 years (because of modern health care, clean water and access to good food, which are all a result of the rocks and minerals we take from the Earth's crust). If we don't mine in one place, the mineral resources needed for society to function will be mined somewhere else. Recycling helps, but as long as global population and standards of living continue to grow, recycling won't replace mining.

11. What is the probability that on your first roll of the dice you stay at the rock at which you start?
The answer is 1/3 or 0.3333 or 33.33% for all four rocks.
For the Intrusive Igneous Rock, rolls of 4, 7, or 10 all have "Go to" as Intrusive Igneous Rock, such that the cumulative probability is, respectively, 3/36 + 6/36 + 3/36 = 12/36 = 1/3.
For the Volcanic Rock, rolls of 4, 8, 10, or 12 all have "Go to" as Volcanic Rock, such that the cumulative probability is, respectively, 3/36 + 5/36 + 3/36 + 1/36 = 12/36 = 1/3.
For the Sedimentary Rock, rolls of rolls of 4, 7, or 10 all have "Go to" as Sedimentary Rock, such that the cumulative probability is, respectively, 3/36 + 6/36 + 3/36 = 12/36 = 1/3.
For the Metamorphic Rock, rolls of rolls of 4, 7, or 10 all have "Go to" as Metamorphic Rock, such that the cumulative probability is, respectively, 3/36 + 6/36 + 3/36 = 12/36 = 1/3.

12. What is the least number of rolls of the dice that are needed to complete this exercise? It will help to examine the rock-cycle diagram and to remember that you also must roll for the number of years at each station. Examining the rock-cycle diagram, there are **Nine.** For example, starting at Volcanic Rock, the first roll is for the number of years to stay there. The second roll would take you to High Temperature & Pressure, and the third roll is for the number of years there. The fourth roll takes you Metamorphic Rock (second rock), and the fifth roll is for the number of years there. The sixth roll takes you to High Temperature & Pressure again, and the seventh roll is for the number of years there. The eighth roll takes you back to Metamorphic Rock again (third rock), and the final, ninth roll is for the number of years there. There are three other scenarios that require only nine rolls. These possible shortest paths are listed in Table 3.

Table 3. Scenarios for completing the exercise with the least number of rolls of the dice.

Start at	Go to	Go to	Go to	Go to
Intrusive Igneous Rock	High T & P	Metamorphic Rock	High T & P	Metamorphic Rock
Volcanic Rock	High T & P	Metamorphic Rock	High T & P	Metamorphic Rock
Sedimentary Rock	High T & P	Metamorphic Rock	High T & P	Metamorphic Rock
Metamorphic Rock	High T & P	Metamorphic Rock	High T & P	Metamorphic Rock

For the next question, possibly for extra credit, students should calculate the probabilities of each of these scenarios. Note that the probabilities for all four of these scenarios are less than 1%; it is unlikely that many students will complete the exercise with few rolls.

Extra Credit

13. For which starting rock do you have the highest probability of completing this exercise with the least number of rolls? Intrusive Igneous Rock. What path does your atom take for this highest probability? Intrusive Igneous Rock to High Temperature & Pressure, then to Metamorphic Rock, then back to High Temperature & Pressure, then, finally, back to Metamorphic Rock.

Ignoring the five rolls needed to determine the numbers of years you stay at each station, there are four rolls involved in moving from one station to the next when completing the exercise with the least number of rolls.

If starting at **Intrusive Igneous Rock**, the least number of rolls could be from Intrusive Igneous Rock to High Temperature & Pressure, then to **Metamorphic Rock** (for the second rock), then back to High Temperature & Pressure, then finally back to **Metamorphic Rock** again (for the third rock). The possible rolls and probabilities for these steps are

Roll 2, 5, or 9, for which Probability (Intrusive Igneous Rock to High Temperature & Pressure) = 1/36 + 4/36 + 4/36 = 9/36 = 1/4.

Roll 4, 7, or 10, for which Probability (High Temperature & Pressure to Metamorphic Rock) = 3/36 +6/36 + 3/36 = 12/36 = 1/3.

Roll 8 or 12, for which Probability (Metamorphic Rock to High Temperature & Pressure) = 5/36 + 1/36 = 6/36 = 1/6.

Therefore the cumulative probability of these four rolls occurring in this sequence equals
1/4 x 1/3 x 1/6 x 1/3 = 1/216 = 0.0046 = 0.46%.

If starting at **Volcanic Rock**, the first roll could be to go from Volcanic Rock to High Temperature & Pressure, then from High Temperature & Pressure to **Metamorphic Rock**, then back to High Temperature & Pressure, then finally back to **Metamorphic Rock**. The possible rolls and probabilities for these steps are:

Roll 7, for which Probability (Volcanic Rock to High Temperature & Pressure) = 6/36 = 1/6.

Roll 4, 7, or 10, for which Probability (High Temperature & Pressure to Metamorphic Rock) = 3/36 +6/36 + 3/36 = 12/36 = 1/3.

Roll 8 or 12, for which Probability (Metamorphic Rock to High Temperature & Pressure) = 5/36 + 1/36 = 6/36 = 1/6.

Therefore, the cumulative probability of these four rolls occurring in this sequence equals
1/6 x 1/3 x 1/6 x 1/3 = 1/324 = 0.0031 = 0.31%.

If starting at **Sedimentary Rock**, the least number of rolls is could be from Sedimentary Rock to High Pressure & Temperature, then to **Metamorphic Rock** (second rock), then back to High Temperature & Pressure, then to **Metamorphic Rock** again (third rock). The possible rolls and probabilities for these steps are

Roll 8 or 12, for which Probability (Sedimentary Rock to High Temperature & Pressure) = 5/36 + 1/36 = 1/6.

Roll 4, 7, or 10, for which Probability (High Temperature & Pressure to Metamorphic Rock) = 3/36 +6/36 + 3/36 = 12/36 = 1/3.

Roll 8 or 12, for which Probability (Metamorphic Rock to High Temperature & Pressure) = 5/36 + 1/36 = 6/36 = 1/6.

Therefore the cumulative probability of these four rolls occurring in this sequence equals
1/6 x 1/3 x 1/6 x 1/3 = 1/324 = 0.0031 = 0.31%.

If starting at **Metamorphic Rock**, the least number rolls could be from Metamorphic Rock to High Temperature & Pressure, then back to **Metamorphic Rock** (for the second rock), then again to High Temperature & Pressure, then finally back to **Metamorphic Rock** (for the third rock). The possible rolls and probabilities for these steps are:

Roll 8 or 12, for which Probability (Metamorphic Rock to High Temperature & Pressure) =
5/36 + 1/36 = 6/36 = 1/6.

Roll 4, 7, or 10, for which Probability (High Temperature & Pressure to Metamorphic Rock) =
3/36 +6/36 + 3/36 = 12/36 = 1/3.

Therefore the cumulative probability of these four rolls occurring in this sequence equals
1/6 x 1/3 x 1/6 x 1/3 = 1/324 = 0.0031 = 0.31%.

The probabilities are summarized in Table 4.

Table 4. Probabilities for scenarios for completing the exercise with the least number of rolls of the dice.

Start at	Go to	Go to	Go to	Go to	Probability
Intrusive Igneous Rock	High T & P	Metamorphic Rock	High T & P	Metamorphic Rock	0.46%
Volcanic Rock	High T & P	Metamorphic Rock	High T & P	Metamorphic Rock	0.31%
Sedimentary Rock	High T & P	Metamorphic Rock	High T & P	Metamorphic Rock	0.31%
Metamorphic Rock	High T & P	Metamorphic Rock	High T & P	Metamorphic Rock	0.31%

Additional Extra Credit

14. Starting as an atom in a volcanic rock, what is the probability that you will

a. be there for 50,000 years, Roll 6 or 12; P = (5+1)/36 = 1/6
b. then go to the Earth's Surface, Roll 2, 5 or 9; P = (1+4+4)/36 = 1/4
c. be there for 500,000 years, Roll 7 or 10; P = (6+3)/36 = 1/4
d. then go to Sediments, Roll 3, 5 or 7; P = (2+4+6)/36 = 1/3
e. be there for 500,000 years, Roll 6 or 12; P = (5+1)/36 = 1/6
f. then go to Compaction and Cementation, Roll 3, 5 or 10; P = (2+4+3)/36 = 1/4
g. be there for 10,000,000 years, Roll 5 or 11; P = (4+2)/36 = 1/6
h. then go to Sedimentary Rock (clastic), Roll 2,4,5,9 or 11; P = (1+3+5+4+2)/36 = 5/12
i. be there for 100,000,000 years, Roll 7; P = 1/6
j. stay there (at Sedimentary Rock) on the next roll, Roll 4, 7 or 10; P = (3+6+3)/36 = 1/3
k. be there for 100,000,000 more years, Roll 7; P = 1/6
l. stay there (at Sedimentary Rock) on the next roll, Roll 4, 7 or 10; P = (3+6+3)/36 = 1/3
m. be there for 100,000,000 more years, Roll 7; P = 1/6
n. then go to High Temperature & Pressure, Roll 8 or 12; P = (5+1)/36 = 1/6
o. be there for 100,000,000 years, Roll 3, 5 or 10; P = (2+4+3)/36 = 1/4
p. then go to Metamorphic Rock, and, finally, Roll 4, 7 or 10; P = (3+6+3)/36 = 1/3
q. be there for 50,000,000 years? Roll 7; P = 1/6

That is, what is the overall probability of all these steps occurring in this sequence?

1/6 x ¼ x ¼ x 1/3 x 1/6 x ¼ x 1/6 x 5/12 x 1/6 x 1/3 x 1/6 x 1/3 x 1/6 x 1/6 x ¼ x 1/3 x 1/6 = 1.2 x 10^{-11} =
0.000000000012 = 0.0000000012%.

Note that this is a small number, which reinforces the fact that many ore deposits are rare relative to the rocks in which they typically occur. A combination of geological processes, at the right place and time, is necessary to form an ore deposit.

Example 3 is one scenario of rolls of the dice by which these steps could have occurred.

This is a practical example. In the end, you will be an atom in a Metamorphic Rock, which, upon examination of Table 1 in the Students' Handout, is the right age to have a Carlin-type gold deposit. This type of ore deposit is named for the town of Carlin, Nevada, near which several of these types of deposits occur. Similar deposits occur in Utah and other parts of the world. The ones in the western United States formed by hot water, laden with gold and sulfur and heated by Eocene magmas related to subduction of oceanic crust beneath the North American Plate. The hot water also altered the sedimentary host rocks by dissolving some minerals and precipitating other minerals. In this activity, we label these "hydrothermally altered" sedimentary rocks as metamorphic, because the high-temperature and somewhat high-pressure process of alteration changed or metamorphosed the original sedimentary rocks.

Additional Notes

Students may question **the path from the Earth's Surface** (where weathering and erosion take place) **to Compaction and Cementation**, without first going through Sediments. One example of this is the formation of a rock called **gossan** (an iron-rich rock resulting from the weathering of sulfide-bearing minerals). Oxygen dissolved in rain water oxidizes sulfide minerals, particularly pyrite (FeS_2), to form sulfuric acid (H_2SO_4), which leaches many of the elements from the original rock (whether sedimentary, igneous, or metamorphic), leaving behind a rock that mostly contains the minerals goethite (FeOOH) and hematite (Fe_2O_3). In this activity, we consider gossan a sedimentary rock. Although it has changed from its original mineralogy and texture, it did not undergo any high-temperature or high-pressure mineralogical or textural changes that form metamorphic rocks.

Another example is a **supergene enrichment blanket**, which sometimes forms at the top of a copper deposit. In this case, copper, which is dissolved by the same weathering process that forms gossan, is redeposited below the groundwater table upon reaction with sulfide minerals. It changes the mineralogy of the rock by depositing copper sulfide minerals (covellite, CuS, and chalcocite, Cu_2S), and it increases the copper grade and value of the ore.

Another example is **hardened laterite** (iron-oxide-rich, silica-poor soil commonly found in tropical climates). Most laterite is unconsolidated soil, but when hardened by cementation with goethite or hematite, it would be considered a rock.

In some instances, particularly in and near ore deposits, it is often difficult to determine what a rock was before it was altered by either hot water or cold water.

Next Generation Science Standards: The most applicable standards are

- High School - History of Earth HS-ESS2-1. Students who demonstrate understanding can develop a model to illustrate how Earth's internal and surface processes operate at different spatial and temporal scales to form continental and ocean-floor features.
- High School – Science and Engineering Practices – Analyzing and Interpreting Data. Apply concepts of statistics and probability to scientific and engineering questions and problems, using digital tools when feasible.
- Middle School – Earth's Systems MS-ESS3-1. Students who demonstrate understanding can construct a scientific explanation based on evidence for how the uneven distribution of Earth's mineral, energy, and groundwater resources are the result of past and current geoscience processes.
- Middle School – Earth's Systems MS-ESS2-1. Students who demonstrate understanding can develop a model to describe the cycling of Earth's materials and the flow of energy that drives this process.
- Disciplinary Core Ideas ESS2.A (Earth Materials and Systems), ESS2.B (Plate Tectonics and Large-Scale Interactions), ESS2.C (The Roles of Water in Earth's Surface Processes), ESS3.A (Natural Resources).

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The next twelve pages are the station labels.

Following those pages are a one-page diagram of the rock cycle and illustrations that help explain where different rock types and ores occur in plate-tectonic settings.

The final pages are for the students, including optional examples of completed rock-cycle data sheets and geologic history sheets.

Intrusive Igneous Rock

Roll:	Number of years:	Roll:	Go to:
2	100,000,000	2	High Temperature & Pressure
3	1,000,000	3	Earth's Surface
4	10,000,000	4	Intrusive Igneous Rock
5	15,000,000	5	High Temperature & Pressure
6	35,000,000	6	Earth's Surface
7	50,000,000	7	Intrusive Igneous Rock
8	100,000,000	8	Melting
9	5,000,000	9	High Temperature & Pressure
10	500,000,000	10	Intrusive Igneous Rock
11	500,000	11	Earth's Surface
12	35,000,000	12	Melting

Adapted by the Education Committee of the Nevada Mining Association from the Lowell Institute for Mineral Resources at the University of Arizona, with funding from the Mining Foundation of the Southwest.

Sedimentary Rock

Roll:	Number of years:	Roll:	Go to:
2	10,000,000	2	Earth's Surface
3	500,000	3	Melting
4	20,000,000	4	Sedimentary Rock
5	1,000,000	5	Melting
6	10,000,000	6	Earth's Surface
7	100,000,000	7	Sedimentary Rock
8	1,000,000	8	High Temperature & Pressure
9	50,000,000	9	Earth's Surface
10	10,000,000	10	Sedimentary Rock
11	500,000,000	11	Earth's Surface
12	500,000	12	High Temperature & Pressure

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Metamorphic Rock

Roll:	Number of years:	Roll:	Go to:
2	500,000,000	2	Melting
3	250,000,000	3	Earth's Surface
4	200,000,000	4	Metamorphic Rock
5	10,000,000	5	Melting
6	100,000,000	6	Earth's Surface
7	50,000,000	7	Metamorphic Rock
8	10,000,000	8	High Temperature & Pressure
9	100,000,000	9	Melting
10	75,000,000	10	Metamorphic Rock
11	500,000,000	11	Earth's Surface
12	250,000,000	12	High Temperature & Pressure

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Volcanic Rock & Volcano
(Extrusive Igneous Rock & Location)

Roll:	Number of years:	Roll:	Go to:
2	100,000	2	Earth’s Surface
3	10,000,000	3	Melting
4	50,000,000	4	Volcanic Rock & Volcano
5	10,000,000	5	Earth’s Surface
6	50,000	6	Melting
7	1,000,000	7	High Temperature & Pressure
8	100,000	8	Volcanic Rock & Volcano
9	10,000	9	Earth’s Surface
10	15,000,000	10	Volcanic Rock & Volcano
11	1,000	11	Melting
12	50,000	12	Volcanic Rock & Volcano

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Magma (Constituent)

Roll:	Number of years:	Roll:	Go to:
2	5,000,000	2	Volcanic Rock & Volcano
3	10,000	3	Cooling & Crystallizing
4	50,000	4	Volcanic Rock & Volcano
5	100,000	5	Cooling & Crystallizing
6	1,000,000	6	Volcanic Rock & Volcano
7	500,000	7	Cooling & Crystallizing
8	5,000,000	8	Volcanic Rock & Volcano
9	75,000	9	Cooling & Crystallizing
10	10,000,000	10	Volcanic Rock & Volcano
11	100,000	11	Cooling & Crystallizing
12	1,000,000	12	Volcanic Rock & Volcano

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Sediments (Constituent)

Roll:	Number of years:	Roll:	Go to:
2	5,000	2	Sediments
3	10,000	3	Compaction & Cementation
4	50,000	4	Water: River/Lake/Ocean
5	100,000	5	Compaction & Cementation
6	500,000	6	Earth's Surface
7	1,000,000	7	Sediments
8	5,000	8	Water: River/Lake/Ocean
9	10,000	9	Earth's Surface
10	5,000,000	10	Compaction & Cementation
11	100,000	11	Sediments
12	500,000	12	Water: River/Lake/Ocean

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Earth’s Surface: Weathering & Erosion (Location & Process)

Roll:	Number of years:	Roll:	Go to:
2	10,000	2	Earth’s Surface
3	100,000	3	Sediments
4	50,000	4	Water: River/Lake/Ocean
5	1,000,000	5	Sediments
6	100,000	6	Earth’s Surface
7	500,000	7	Sediments
8	10,000	8	Water: River/Lake/Ocean
9	1,000,000	9	Compaction & Cementation
10	500,000	10	Earth’s Surface
11	100,000	11	Compaction & Cementation
12	1,000,000	12	Water: River/Lake/Ocean

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Cooling & Crystallizing
(Process)

Roll:	Number of years:	Roll:	Go to:
2	10,000	2	Intrusive Igneous Rock
3	500,000	3	Cooling & Crystallizing
4	750,000	4	Intrusive Igneous Rock
5	500,000	5	Cooling & Crystallizing
6	100,000	6	Intrusive Igneous Rock
7	250,000	7	Cooling & Crystallizing
8	10,000	8	Melting
9	500,000	9	Intrusive Igneous Rock
10	100,000	10	Melting
11	500,000	11	Intrusive Igneous Rock
12	100,000	12	Melting

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High Temperature & Pressure (Process)

Roll:	Number of years:	Roll:	Go to:
2	10,000,000	2	High Temperature & Pressure
3	100,000,000	3	Melting
4	50,000,000	4	Metamorphic Rock
5	100,000,000	5	Melting
6	10,000,000	6	High Temperature & Pressure
7	150,000,000	7	Metamorphic Rock
8	50,000,000	8	High Temperature & Pressure
9	200,000,000	9	Melting
10	100,000,000	10	Metamorphic Rock
11	200,000,000	11	Melting
12	50,000,000	12	High Temperature & Pressure

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Compaction & Cementation (Process)

Roll:	Number of years:	Roll:	Go to:
2	10,000	2	Sedimentary Rock (clastic)
3	50,000	3	Compaction & Cementation
4	500,000	4	Sedimentary Rock (clastic)
5	10,000,000	5	Compaction & Cementation
6	15,000,000	6	Sedimentary Rock (clastic)
7	100,000	7	Compaction & Cementation
8	10,000	8	High Temperature & Pressure
9	50,000	9	Sedimentary Rock (clastic)
10	1,000,000	10	High Temperature & Pressure
11	10,000,000	11	Sedimentary Rock (clastic)
12	15,000,000	12	High Temperature & Pressure

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Water: River/Lake/Ocean
(Location & Process—dissolution/precipitation)

Roll:	Number of years:	Roll:	Go to:
2	10,000	2	Water: River/Lake/Ocean
3	1,000,000	3	Sediments
4	500,000	4	Sedimentary Rock (chemical)
5	5,000	5	Sediments
6	10,000	6	Compaction & Cementation
7	50,000	7	Water: River/Lake/Ocean
8	100,000	8	Sedimentary Rock (chemical)
9	1,000	9	Compaction & Cementation
10	10,000	10	Sediments
11	5,000	11	Water: River/Lake/Ocean
12	100,000	12	Sedimentary Rock (chemical)

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Melting
(Process)

Roll:	Number of years:	Roll:	Go to:
2	20,000	2	Melting
3	5,000,000	3	Magma
4	50,000	4	Cooling & Crystallizing
5	100,000	5	Magma
6	1,000,000	6	Cooling & Crystallizing
7	500,000	7	Melting
8	100,000	8	Magma
9	5,000,000	9	Cooling & Crystallizing
10	10,000	10	Magma
11	20,000	11	Melting
12	1,000,000	12	Magma

Adapted by the Education Committee of the Nevada Mining Association from the Lowell Institute for Mineral Resources at the University of Arizona, with funding from the Mining Foundation of the Southwest.

The following page is the rock-cycle diagram.

The final color pages can be used in a PowerPoint presentation or overhead projection to explain where different rock types and ores occur in plate-tectonic settings.

The following pages are to give to the students.

Rock Cycle and Mineral Deposits

The rock cycle helps us understand and visualize how rocks and minerals on Earth change from one rock type to another (igneous, metamorphic, and sedimentary). The theory of plate tectonics explains the details of the rock cycle and helps us understand the mechanisms and processes that move rocks and minerals through the cycle. This exercise is designed to extend your understanding of both the rock cycle and plate tectonics. It will also provide you with insight into the formation of mineral and rock deposits (ores) on which we depend for the materials we use in our daily lives. Beginning with the alarm clock that awakens us to the light bulbs that illuminate the room before we go to bed, everything we use is made with, made by, or processed by the materials that come from mines. In this exercise we are focusing on a few types of ores that are mined in the United States: sand and gravel and placer gold in unconsolidated sediments; barite, diatomite, gypsum, iron, lead, limestone, phosphate, potash, salt, uranium, and zinc in sedimentary rocks; hydrothermal gold in volcanic rocks; porphyry copper and molybdenum, platinum, and rare-earth-element deposits in intrusive igneous rocks, and Carlin-type (also hydrothermal) gold and crushed stone deposits in metamorphic rocks.

Procedure:

Working with a partner, you will ride the rock cycle recording your route and creating your geologic history. Then determine whether you may have ever been an ore deposit.

1. Work in teams of two. Each team starts at a **rock station** – either **volcanic rock**, **intrusive igneous rock**, **metamorphic rock**, or **sedimentary rock**. Consider yourself a small piece of that rock—an atom in one of the minerals in the initial rock. Although you'll remain the same atom (unless you were radioactive), you'll be changed into different solid, liquid, or gaseous forms as you move through the rock cycle.
2. Record the rock type on the **rock-cycle data sheet**. Roll the dice, record the total number rolled (possible numbers are 2 through 12) and the corresponding number of years on the first line of the rock-cycle data sheet.
3. Roll the dice again, record the total number rolled and where that roll is taking you ("Go to") on the second line of the rock-cycle data sheet. Note that it could be where you already are. Also **circle** on this line whether this is a **Process, Location, Constituent, and/or Rock**. Processes include **compaction and cementation** (converting loose, unconsolidated sediment, shells, or rock fragments into solid rock), **high temperature and pressure** (generally achieved with deep burial, thrusting of one package of rocks on top of another, or subduction in an oceanic trench), **melting** (either deep in the crust or mantle or near the surface), **cooling and crystallization**, **weathering and erosion** (at the Earth's surface, driven largely by energy from the Sun), and **dissolution and precipitation** (occasionally resulting in chemical sedimentary rocks, including gypsum, halite, barite, and some limestones).
4. If you are going to another station, go to that station.
5. If you have rolled a total number that keeps you at your current station, roll the dice again, and record the number of years you will be there on the same line.
6. If you have moved to another station, roll the dice when you get there to determine how long you are staying at that station (and record that number of years on the same line).
7. Continue to roll and record your data in this manner (repeating steps 3 through 6) until you have become three separate rocks. You start out as a rock, go through some processes, become another rock, go through additional processes, and become a final (third) rock. Be sure to roll a final time to determine how long you stay as this final rock. Keep in mind that you may stay at a particular station through multiple rolls. (See the **example rock-cycle data**

sheets that are attached.) If you are running out of space on your data sheet, you can use the "Sediments" station as one of your three rocks. Some teams will finish before others, as their cycle may be shorter than others. That is okay.

8. Once you have data for three different rocks, sit back at your desk and write up the geologic history of the rocks on the **geologic history sheet**, using your rock-cycle data sheet.
9. Understand that the rock station where you ended is the rock that you are right now (the present); it is the **youngest** rock. Its age is from the present to however many years you rolled in the last roll on the data sheet. (See the **example geologic history sheets** that are also attached. Essentially the geologic history turns the rock-cycle data sheet upside down. Start at the bottom and work your way up.) The **oldest** rock in your geologic history will be the rock at which you started.
10. If you stayed at one station multiple times, add the number of years at which the dice indicated that you stayed at that station. This combination will be what you enter on your geologic history sheet.
11. Record the youngest rock (where you ended) at the top of the geologic history sheet and write the number of years you stayed as this final rock.
12. Work your way from the bottom of the rock-cycle data sheet, one station at a time. On the geologic history sheet, record the station and the number of years that you were at that station. The rock at which you started (the oldest rock) will be on the bottom of the geologic history sheet.
13. To determine the geologic age of each of your rocks, you will need to do some addition. The youngest rock's age is from present to the number of years on the top line of the geologic history sheet. Record this at the bottom of the sheet on the line for the youngest rock.
14. Now determine the age of the middle rock. Add all the years from the top of the geologic history sheet down to the line just above where that rock shows. This is the youngest age for that rock. Now add the number of years that rock existed to this number, and you have the oldest date for the middle rock. Record the name of this (middle) rock type and those two numbers on the line for the middle rock on the geologic history sheet. The age of the oldest rock is determined by adding all the years on the geologic history sheet except the number of years on the last line, which is the youngest age that the oldest rock was. Finally, add the last line of years to those years; this is the final age of the oldest rock.
15. Whew…now you have data that you can interpret to see whether one or more of your rocks may have been a rock that could be mined!
16. To determine if one of your rocks could also be an **ore** (a rock that can be mined profitably), look at the rock types and their ages listed in Table 1. Compare these rock types and ages with your data.

Interpretation:

1. Where did you spend most of your time? ____
2. Why do scientists call the rock cycle a cycle? ____
   ____
3. Where do weathering and erosion occur? ____
4. List the processes that move rocks through the rock cycle. ____________________________
   ____
5. Explain the forces or sources of energy that create these processes. ______________________
   ____
   ____
6. If you were at the Earth's surface, what type of rock were you when you got there? ________
   ____

Generally, a rock must be at or near (within a few kilometers of) the Earth's surface to be considered an ore—a rock that can be profitably mined. To figure out whether your rocks may have also been an ore deposit, determine whether your rock was present at one of the times in Table 1. For example, if you were an intrusive igneous rock between 35,000,000 and 100,000,000 years ago (35 to 100 Ma), you could have formed a porphyry copper deposit (like ones in Arizona, Montana, Nevada, New Mexico, and Utah).

Table 1. Examples of ores in the United States of America.

Rock type or constituent	Type of ore	Age range*	Location[#]
Sediments	Sand and gravel	<10,000 years ago (Holocene)	H A W C E
Sediments	Placer gold	<5.3 Ma (Holocene to Pliocene)	A W E
Sedimentary rock (clastic)	Diatomite	5.3 to 23 Ma (Miocene)	W
Sedimentary rock (chemical)	Gypsum & Salt	5.3 to 23 Ma (Miocene)	W
		or 145 to 201 Ma (Jurassic)	W C
		or 252 to 299 Ma (Permian)	W C
		or 419 to 445 Ma (Silurian)	E
Sedimentary rock (chemical)	Phosphate	2.6 to 23 Ma (Pliocene to Miocene)	E
		or 252 to 299 Ma (Permian)	W
Sedimentary rock (chemical)	Potash/potassium	252 to 299 Ma (Permian)	W
Sedimentary rock (clastic)	Uranium	5.3 to 201 Ma (Miocene to Jurassic)	W C
Sedimentary rock (clastic)	Coal	299 to 323 Ma (Pennsylvanian)	C E
		or 34 to 144 Ma (Eocene to Cretaceous)	W
Sedimentary rock (chemical)	Barite	359 to 419 Ma (Devonian)	W
Sedimentary rock (chemical or clastic)	Limestone	252 to 541 Ma (Paleozoic)	A W C E
Sedimentary rock (chemical or clastic)	Lead and zinc	252 to 419 Ma (Permian to Devonian)	A C E
Sedimentary rock (chemical)	Iron	1,600 to 2,500 Ma (Paleoproterozoic)	C
Volcanic rock	Hydrothermal gold	2.6 to 56 Ma (Pliocene to Eocene)	A W
Intrusive igneous rock	Porphyry copper	34 to 201 Ma (Eocene to Jurassic)	A W
Intrusive igneous rock	Porphyry molybdenum	23 to 56 Ma (Oligocene to Eocene)	W
Intrusive igneous rock	Platinum	2,500 to 4,000 Ma (Archean)	W
		or 1,000 to 1,600 Ma (Mesoproterozoic)	C
Intrusive igneous rock	Rare earth elements	1,000 to 1,600 Ma (Mesoproterozoic)	W
Metamorphic rock	Carlin-type gold	34 to 56 Ma (Eocene)	W
Metamorphic rock	Crushed stone (gneiss)	>541 Ma (Precambrian)	W C E

***** Ma = millions of years ago. # H = Hawaii; A = Alaska; W = western, C = central, E = eastern United States.

7. Look at your data. Pay attention to where you are located geographically (either Alaska, Hawaii, or the western, central, or eastern conterminous United States. Could you have formed any of the above ore deposits? If so, which ones?

8. Assuming that you did form an ore deposit, was the deposit preserved and located near the surface so that it can now be mined? Or was the deposit weathered and eroded away in the years after it formed?

9. Take a survey in your class and list the number and types of ore deposits formed through this activity by everyone in the class.

10. Did this exercise help you understand how infrequently economic accumulations or rocks and minerals occur? _____ Explain. ____
____
____

11. What is the probability that on your first roll of the dice you stay at the rock at which you start? ____________________

To answer this question, you need to know the probabilities of possible rolls of the dice. The probability of any one of the six numbers on a six-sided die is 1/6 or 0.1667 or 16.67% (rounded to four significant figures), assuming that the die isn't loaded (weighted so that one number preferentially is rolled) or damaged such that the roll is not random.

The probability of one event occurring **and** a second event occurring is equal to the probability of the first event occurring **multiplied** by the probability of the second event occurring. Therefore the probability of rolling, for example, a 1 with the first die and a 1 with the second die is 1/6 x 1/6 = 1/36. Similarly, the probability of rolling a 1 with the first die and a 2 with the second die is 1/6 x 1/6 = 1/36, and the probability of rolling a 2 with the first die and a 1 with the second die is also 1/6 x 1/6 = 1/36.

The probability of one event occurring **or** a second event occurring is equal to the probability of the first event occurring **added** to the probability of the second event occurring. Therefore the probability of rolling a total of 3 with one roll of two dice is 1/36 + 1/36 = 2/36. Using the same rules, Table 2 lists the probabilities for the eleven possible numbers that can be rolled with two dice.

Table 2. Probabilities of possible rolls of two six-sided dice.

Role	Possible combinations of dice	Probability
2	1 & 1	1/36
3	1 & 2 or 2 & 1	2/36
4	1 & 3 or 3 & 1 or 2 & 2	3/36
5	1 & 4 or 4 & 1 or 2 & 3 or 3 & 2	4/36
6	1 & 5 or 5 & 1 or 2 & 4 or 4 or 2 or 3 & 3	5/36
7	1 & 6 or 6 & 1 or 2 & 5 or 5 & 2 or 3 & 4 or 4 & 3	6/36
8	2 & 6 or 6 & 2 or 3 & 5 or 5 & 3 or 4 & 4	5/36
9	3 & 6 or 6 & 3 or 4 & 5 or 5 & 4	4/36
10	4 & 6 or 6 & 4 or 5 & 5	3/36
11	5 & 6 or 6 & 5	2/36
12	6 & 6	1/36

12. What is the least number of rolls of the dice that are needed to complete this exercise? It will help to examine the rock-cycle diagram and to remember that you also must roll for the number of years at each station.________________________

13. For which starting rock do you have the highest probability of completing this exercise with the least number of rolls? ___________________ What path does your atom take for this highest probability? ____
____

14. Starting as an atom in a volcanic rock, what is the probability that you will

a. be there for 50,000 years, ______________________________
b. then go to the Earth's Surface, ______________________________
c. be there for 500,000 years, ______________________________
d. then go to Sediments, ______________________________
e. be there for 500,000 years, ______________________________
f. then go to Compaction and Cementation, ______________________________
g. be there for 10,000,000 years, ______________________________
h. then go to Sedimentary Rock (clastic), ______________________________
i. be there for 100,000,000 years, ______________________________
j. stay there (at Sedimentary Rock) on the next roll, ______________________________
k. be there for 100,000,000 more years, ______________________________
l. stay there (at Sedimentary Rock) on the next roll, ______________________________
m. be there for 100,000,000 more years, ______________________________
n. then go to High Temperature & Pressure, ______________________________
o. be there for 100,000,000 years, ______________________________
p. then go to Metamorphic Rock, and, finally, ______________________________
q. be there for 50,000,000 years? ______________________________

That is, what is the overall probability of all these steps occurring in this sequence?

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Example 3 is one scenario of rolls of the dice by which these steps could have occurred.

This is a practical example. In the end, you will be an atom in a Metamorphic Rock, which, upon examination of Table 1, is the right age to have a Carlin-type gold deposit. This type of ore deposit is named for the town of Carlin, Nevada, near which several of these types of deposits occur. Similar deposits occur in Utah and other parts of the world. The ones in the western United States formed by hot water, laden with gold and sulfur and heated by Eocene magmas related to subduction of oceanic crust beneath the North American Plate. The hot water also altered the sedimentary host rocks by dissolving some minerals and precipitating other minerals. In this activity, we label these "hydrothermally altered" sedimentary rocks as metamorphic, because the high-temperature and somewhat high-pressure process of alteration changed or metamorphosed the original sedimentary rocks.