

Crystal Size Versus Cooling Time, and What a Dice Game Says About Rock

Learning target: I can graph and calculate from data to show how cooling time controls crystal size, and I can use a tally from a rock-cycle game to judge what the game models well and poorly.

Data and graphing About 45 min Individual MS-ESS2-1 · practice data analysis independent practice

Standards connections

MS-ESS2-1 (practice): Part A quantifies crystallization, one of the processes the PE names, so students can reason about intrusive versus extrusive rock from numbers. Part B asks students to evaluate a physical model of the cycle, which builds the modeling practice the PE requires without being the student's own model.

Purpose: practice · **Time:** about 45 minutes · **Format:** individual

Answers with reasoning

Part A: How does cooling time change crystal size?

A science class melted a safe, low-melting-point solid in a warm water bath and let samples cool for different lengths of time before the crystals stopped growing. Students measured the ten largest crystals in each sample under a hand lens and recorded the average length. Two trials were run for every cooling time. The melt is a stand-in for magma: it is not rock, but its crystals grow by the same rule.

Average crystal length after different cooling times (teaching dataset)

Simulated teaching dataset: the numbers are invented to be realistic, not measured.

Cooling time (hours)	Trial 1: average crystal length (mm)	Trial 2: average crystal length (mm)
2	0.6	0.5
4	1.1	1.2
6	1.8	1.6
8	2.3	2.2
10	2.7	2.9
12	3.4	3.3

Simulated data for teaching. The pattern, not the exact numbers, is what matters.

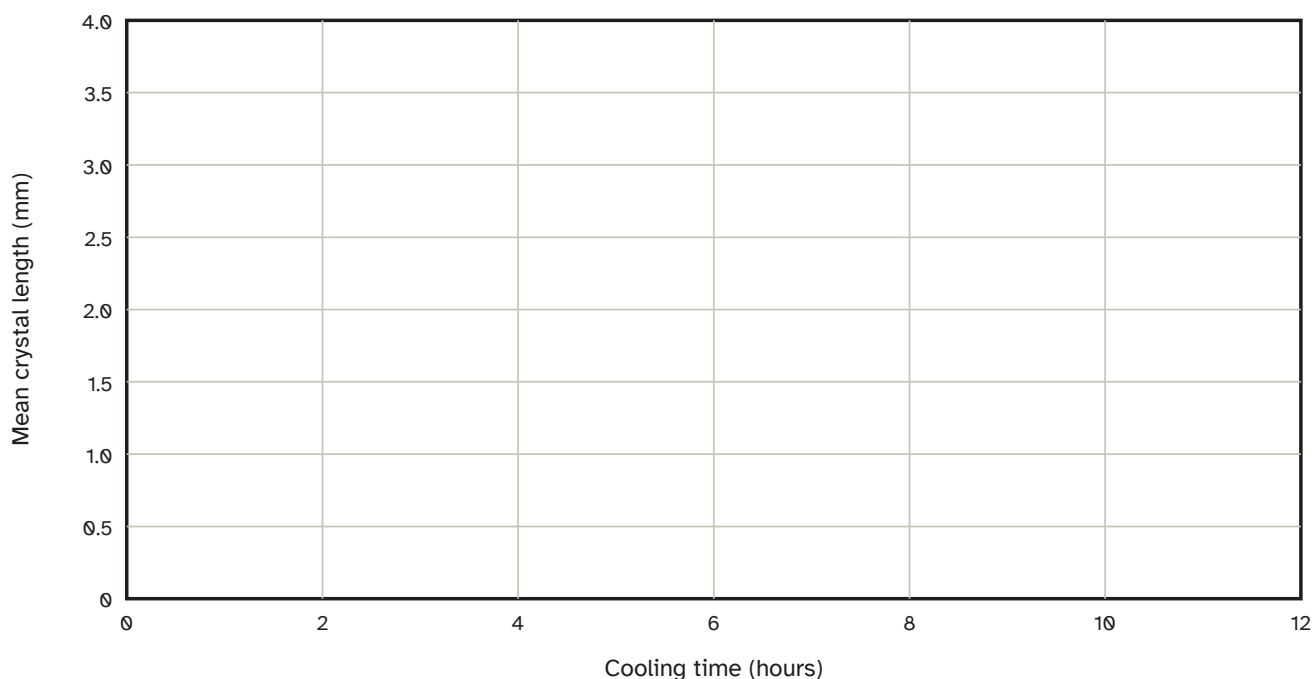
1. For each cooling time, calculate the mean of Trial 1 and Trial 2. Show one calculation below the table.

Answer: 2 h: $(0.6 + 0.5) \div 2 = 0.55$ mm. 4 h: $(1.1 + 1.2) \div 2 = 1.15$ mm. 6 h: $(1.8 + 1.6) \div 2 = 1.7$ mm. 8 h: $(2.3 + 2.2) \div 2 = 2.25$ mm. 10 h: $(2.7 + 2.9) \div 2 = 2.8$ mm. 12 h: $(3.4 + 3.3) \div 2 = 3.35$ mm.

Why: Each mean is the sum of the two trials divided by 2. The trials agree within 0.2 mm, so averaging smooths small measurement differences.

Also acceptable: Accept means rounded to one decimal place (0.6, 1.2, 1.7, 2.3, 2.8, 3.4) if the student says they rounded.

Mean crystal length versus cooling time



2. Calculate how fast the crystals grew, in millimeters per hour, using the means at 2 hours and 12 hours. Show your work.

Answer: Change: $3.35 \text{ mm} - 0.55 \text{ mm} = 2.80 \text{ mm}$. Time: $12 \text{ h} - 2 \text{ h} = 10 \text{ h}$. Rate: $2.80 \text{ mm} \div 10 \text{ h} = 0.28 \text{ mm per hour}$.

Why: Rate is change in size over elapsed time. Using the end points of the data keeps the calculation simple; the line of best fit has nearly the same slope.

Also acceptable: Accept 0.28 mm/h; accept 0.3 mm/h if rounded. A student who used rounded means ($3.4 - 0.6 = 2.8$) gets the same rate.

3. Describe the shape of your graph. What does it tell you about the relationship between cooling time and crystal size?

Answer: The points lie close to a straight line rising to the right. The longer the melt took to cool, the larger its crystals grew, and in this model the growth was steady: about the same extra length for every extra hour.

Why: A linear shape means a constant growth rate in this teaching dataset. The key science conclusion is 'more cooling time, bigger crystals.'

Also acceptable: Accept 'the crystals grow about 0.56 mm every 2 hours.'

- Describes a rising, roughly straight line
- States that crystal size increases with cooling time

4. Predict the mean crystal length after 24 hours if the pattern continues. Show the calculation.

Answer: From the 12-hour mean: $3.35 \text{ mm} + (0.28 \text{ mm/h} \times 12 \text{ h}) = 3.35 \text{ mm} + 3.36 \text{ mm} = 6.71 \text{ mm}$, about 6.7 mm. (Using the rate from zero: $0.28 \text{ mm/h} \times 24 \text{ h} = 6.72 \text{ mm}$, the same to one decimal.)

Why: Either extending from the last data point or multiplying the rate by 24 hours is valid because the line passes almost through the origin.

Also acceptable: Accept 6.7 to 6.8 mm with the work shown; accept 7 mm if the student used 0.3 mm/h ($0.3 \times 24 = 7.2 \text{ mm}$).

5. The class melt is a model of magma. Give one way it is like magma and one way it is not. Say how the difference might affect how far you can trust the 24-hour prediction for real rock.

Answer: Like magma: it is a melted material in which crystals start small and grow larger the longer cooling lasts. Unlike magma: it is a single pure substance at a low temperature in a water bath, while magma is a hot mixture of many minerals that cools over years to millions of years deep underground. Because real magma grows several minerals at once and cools under pressure, the exact rate would differ, so the 24-hour prediction is reliable for the class melt but only the pattern (longer cooling, bigger crystals), not the number, transfers to rock.

Why: Students should separate the transferable rule from the non-transferable numbers.

Also acceptable: Accept 'it cools in hours, magma cools in thousands of years' as the difference.

- One valid similarity (melt that crystallizes; size depends on time)
- One valid difference (temperature, mixture, timescale or pressure)
- Says the pattern transfers but the exact numbers do not

One common grain-size scale for igneous rocks (reference values; cut-offs vary a little between textbooks)

Texture name	Typical crystal size	Usual meaning
Glassy	No crystals large enough to see; mostly glass	Cooled almost instantly, as in an explosive eruption
Fine-grained	Crystals smaller than about 1 mm	Cooled quickly at or near the surface (extrusive)
Medium-grained	About 1 mm to 5 mm	Cooled at a moderate rate, often in a shallow intrusion
Coarse-grained	Larger than about 5 mm	Cooled slowly, deep underground (intrusive)

6. Using the reference scale and your means from q1, which cooling times in the class model would count as fine-grained, and which as medium-grained? Did any sample reach coarse-grained?

Answer: Fine-grained (under about 1 mm): the 2-hour sample (0.55 mm). Medium-grained (about 1 to 5 mm): the 4, 6, 8, 10 and 12-hour samples (1.15 to 3.35 mm). No sample reached coarse-grained (over 5 mm).

Why: Reading the means against the reference cut-offs.

Also acceptable: If the student rounded 1.15 mm down to 1 mm and called 4 h 'borderline', accept with the explanation.

- 2 h classed as fine
- 4-12 h classed as medium
- States none are coarse

7. Using your growth rate from q2, calculate about how many hours the melt would need to reach the coarse-grained boundary of 5 mm. Show your work.

Answer: $5 \text{ mm} \div 0.28 \text{ mm per hour} = 17.9 \text{ hours}$, about 18 hours.

Why: Dividing the target length by the growth rate gives the time, assuming the line runs through the origin, which the data support.

Also acceptable: Accept 17 to 18 hours; a student extending from 12 h gets $(5 - 3.35) \div 0.28 = 5.9 \text{ h}$ more, so about 17.9 h, the same answer. Accept 16.7 h if the student used 0.3 mm/h.

8. A geologist finds two igneous rocks: Rock 1 has crystals about 0.1 mm across; Rock 2 has crystals about 8 mm across. Using the pattern in your data and the reference scale, explain which rock cooled faster, where each probably cooled, and why 'faster' does not mean the cooling happened in a few hours for real rock.

Answer: Rock 1 (0.1 mm) cooled much faster than Rock 2 (8 mm). In the data, small crystals go with short cooling times and large crystals with long ones. Rock 1 is fine-grained, so it probably cooled at or near the surface as lava, an extrusive rock. Rock 2 is coarse-grained, so it cooled slowly deep underground, insulated by surrounding rock, an intrusive rock. 'Faster' is relative: a lava flow can take days to years to harden, and a large intrusion can take thousands to millions of years. The class melt reaches these sizes in hours because it is a different substance at a low temperature, so only the comparison, not the clock time, carries over to rock.

Why: Full credit links each rock to its cooling speed and setting and recognizes that real timescales are far longer than the model's.

Also acceptable: Naming basalt and granite is acceptable but not required.

- Rock 1 cooled faster, Rock 2 slower
- Rock 1 placed at the surface (extrusive), Rock 2 underground (intrusive)
- Explains that real cooling takes far longer than the model's hours

Part B: What a rock-cycle dice game can and cannot show

A class of 24 students played a rock-cycle game. Each student started at a station (magma, igneous rock, sediment, sedimentary rock or metamorphic rock), rolled a die, and followed a rule card that said whether to stay or which station to move to. Every student rolled ten times, for 240 rolls in total. The tally below records what happened at each station.

Tally of 240 rolls in the rock-cycle game (teaching dataset)

Simulated teaching dataset: the numbers are invented to be realistic, not measured.

Station	Rolls made there	Stayed	Moved to magma	Moved to igneous	Moved to sediment	Moved to sedimentary	Moved to metamorphic
Magma	40	20	0	20	0	0	0
Igneous rock	48	24	4	0	5	0	15
Sediment	44	22	0	0	0	22	0
Sedimentary rock	48	24	4	0	3	0	17
Metamorphic rock	60	30	13	0	17	0	0

Simulated data for teaching. 'Stayed' means the roll told the student to remain at the same station for another turn.

9. Calculate the total number of 'stay' rolls and what percentage of all 240 rolls that is. What idea about real rock do you think the game designer was trying to build in with so many 'stay' results?

Answer: Stayed total: $20 + 24 + 22 + 24 + 30 = 120$ rolls. Percentage: $120 \div 240 \times 100 = 50$ percent. The designer built in the idea that rock spends most of its existence not changing: a piece of granite or sandstone can sit for millions of years before anything moves it to another stage.

Why: Half of all rolls were 'stay', which represents the long stable periods between changes.

Also acceptable: Accept 'rocks do not change very often' as the interpretation.

- Total 120 and 50 percent with the calculation
- Interprets 'stay' as rock remaining unchanged for long periods

10. Name the process that each of these moves stands for: igneous rock to sediment; sediment to sedimentary rock; sedimentary rock to metamorphic rock; metamorphic rock to magma.

Answer: Igneous rock to sediment: weathering and erosion. Sediment to sedimentary rock: deposition followed by compaction and cementation. Sedimentary rock to metamorphic rock: heat and pressure (deformation or recrystallization) without melting. Metamorphic rock to magma: melting.

Why: Each move corresponds to exactly one rock-cycle process or process pair.

Also acceptable: Accept 'burial and cementing' for the sediment step and 'metamorphism' for the heat-and-pressure step.

- All four processes correct

11. Using only moves that appear in the tally, write the shortest route from sedimentary rock to igneous rock, and name the process on each step. What does the existence of this route show about the rock cycle?

Answer: Sedimentary rock → magma (melting) → igneous rock (cooling and crystallization). Two moves. The route shows that a rock does not have to pass through every stage in order; any rock type can reach any other, which is why the rock cycle is a web of possible paths rather than a single loop.

Why: The tally contains the sedimentary-to-magma move (4 rolls) and the magma-to-igneous move (20 rolls). The three-step route through metamorphic rock is also valid but not the shortest.

Also acceptable: Accept the three-step route through metamorphic rock if the student explains it is longer than the two-step route.

- Route sedimentary → magma → igneous
- Processes named (melting; cooling/crystallization)
- States that any rock can become any other / no fixed order

12. There is no move from metamorphic rock straight to igneous rock, and none from igneous rock straight to sedimentary rock. Explain why the game is right to leave those out.

Answer: Metamorphic rock cannot become igneous rock without first melting into magma, because igneous rock by definition crystallizes from a melt; so the only route is through the magma station. Igneous rock cannot become sedimentary rock without first being broken into sediment by weathering, then deposited, compacted and cemented; so the only route is through the sediment station. The game is modeling that these two changes require an in-between material.

Why: This checks the definitions: igneous rock needs a melt; sedimentary rock needs sediment (or dissolved material).

Also acceptable: A student who notes that dissolved material from chemical weathering is also 'sediment' in the game's sense is reasoning well.

- Explains that igneous rock requires melting first
- Explains that sedimentary rock requires sediment first

13. Metamorphic rock had the most rolls (60). A student concludes, 'So most of Earth's rock must be metamorphic.' Explain why the tally cannot support that conclusion, and describe one change to the game that would make it a better model of how long rock really spends at each stage.

Answer: The number of rolls at a station depends on the game's rule cards and dice, not on how much of each rock exists on Earth: the metamorphic station had the most rolls partly because many cards send players there and half the rolls say 'stay'. A tally of a game cannot measure the real amounts of rock. A better model would give each station a different amount of time per roll: for example, one roll at the magma station might stand for a thousand years while one roll at the sedimentary-rock station might stand for ten million years, so that staying at some stations represents far longer than staying at others. Another improvement would be to set the dice probabilities from real estimates of how often each change happens.

Why: The answer must separate the game's frequencies from reality and propose a change that makes time per station realistic.

Also acceptable: Accept 'give each station a different number of stay faces on the die' as the improvement.

- States that the tally reflects the rules, not Earth's rock amounts
- Proposes a change that makes time per station (or move probabilities) more realistic

Teacher notes

Part A's melt is deliberately unnamed; if the class has seen a salol (phenyl salicylate) crystal-growth demonstration, say the data are shaped like what such a model produces but were not measured from it; crayon wax (Lab 1) does not grow visible crystals. The linear growth is a teaching simplification; real crystal growth slows as the melt is used up and depends on composition and water content (pegmatites grow giant crystals from water-rich magma without unusually slow cooling), so the rule taught here is 'in this model, longer cooling makes bigger crystals,' the main control in the lesson. The grain-size table uses widely published cut-offs (about 1 mm and 5 mm) but schemes differ, hence the hedge in the title. Part B's tally sums to 240 by design; check q9 against 120. The tally is internally consistent: at every station, moves in plus students who started there equal moves out plus students who ended there, and metamorphic rock receives the most moves (32), which is why it has the most rolls. The missing direct moves in q12 are intentional and correct. If students ask whether magma can go straight to sediment, point out that lava weathering at the surface is igneous rock to sediment, which the game includes.

Scaffold offered to students: Rates in two steps

A rate is a change divided by the time it took. Step 1: subtract to find the change (for q2, the mean at 12 hours minus the mean at 2 hours). Step 2: divide by the time between them ($12 - 2 = 10$ hours). The unit is millimeters per hour. For a percentage (q9), divide the part by the whole and multiply by 100: $\text{part} \div 240 \times 100$. For q7, you are asking 'how many hours at this rate make 5 mm?', so divide 5 mm by the rate.

Extension: Redesign the rule cards

Rewrite the rule card for the sediment station so that it includes two routes the current game lacks: dissolved material crystallizing straight into rock (chemical sedimentation) and sediment being carried farther before it is deposited. Decide what die rolls trigger each route and write a one-sentence justification for each probability you chose. Then predict how your new card would change the 'stayed' percentage for the sediment station after 44 rolls, and explain whether that change makes the model more or less realistic.