

The Quarry Case File: Order the Events and Bracket the Ages

Investigation question: From a set of field observations about one quarry wall, what order of events can be proven, which pairs of events cannot be ordered, and how old can each layer be shown to be?

Evidence-based mystery

Groups of 4

1 session

Setup 5 · Activity 40 · Cleanup 3 min

MS-ESS1-4 · assesses

MS-ESS2-2 · supports

Scientific purpose

Students receive twelve evidence cards describing a tilted, faulted and intruded stack of layers with two dated volcanic ash beds and a dated dike. Working in two rounds, first with the layer cards and then with the structural cards, they build the sequence of events, attach a rule and a card to every step, bracket each layer's age in years, and identify the one pair of events the evidence cannot order. The case is invented for teaching but every rule and every age-bracketing move is the real method.

Why this helps students with this chapter

A cross section in a textbook comes with the answer printed beside it. A case file does not: students must decide which observation justifies which step and must notice when the evidence runs out. Splitting the cards into two rounds makes the method visible, first the stacking rules, then the cutting rules, and the dated ash beds turn the order into numbers, which is the move the textbook mentions but never shows.

Standards connections

MS-ESS1-4 (assesses, constructing an explanation of the relative order of events from rock-strata evidence, including fossils and dated igneous layers; not the organization of the geologic time scale itself): A Grade 8 PE in California's integrated sequence. The written sequence with a rule and evidence card for each step, plus the age brackets, is direct evidence that students can construct an explanation from rock-strata evidence. No period or epoch names are used, so the assessment boundary is respected; the time-scale half of the PE belongs to Lesson 9.

MS-ESS2-2 (supports, recognizing deposition, tilting, faulting, intrusion and erosion as processes that changed one place over time): The sequence students build is a history of geoscience processes acting on one spot at very different rates, from an ash fall in hours to deposition over millions of years, which supports explanations of surface change at varying time scales.

Roles (rotate each session)

- **Card reader:** Reads each evidence card aloud, exactly as written, and keeps the cards in play laid out where everyone can see them.
- **Sequencer:** Moves the event sticky notes on the group's timeline strip as the group argues, and does not move one without a card being cited.

- **Rule checker:** For every move, names the rule (superposition, original horizontality, lateral continuity, cross-cutting relationships, fossil succession) and challenges moves that have no rule behind them.
- **Recorder:** Writes the agreed sequence, rules and card numbers on the recording sheet and fills in the age-bracket table.

Materials

Item	Quantity	Per	Note
Evidence card set (12 cards), printed and cut	1 set	group	The card text is in the recording sheet's cards block; print it two-up on card stock.
Cross-section figure (the two diagrams on the recording sheet, enlarged)	1	group	
Sticky notes for the event timeline (one per event, 11 or 12)	12	group	
Timeline strip: a sheet of paper with an arrow labeled OLDEST to YOUNGEST	1	group	
Rule reference strip (the five rules, each phrased as a question)	1	student	
Recording sheet and pencil	1	student	
Calculator	1	group	

Estimated cost: 3 to 5 per class (an estimate; Card stock and printing for eight card sets, plus one pad of sticky notes. Everything else is ordinary classroom paper.)

Safety

- No physical hazards beyond ordinary classroom materials. If groups cut their own cards, scissors are used seated and passed handle first.

Teacher preparation and setup

1. Print and cut the twelve evidence cards for each group; number them on the back. Put cards 1 to 7 in one envelope labeled Round 1 and cards 8 to 12 in a second envelope labeled Round 2.
2. Print the rule reference strip: Superposition (What is on top of what?), Original horizontality (Is it flat? If not, it was moved later), Lateral continuity (Does it match across the gap?), Cross-cutting (What does it cut? It is younger than that), Fossil succession (Which fossils, and in what order?).
3. Pre-write the event sticky notes for groups that need more support: Sandstone S deposited, Shale H1 deposited, Ash V1 falls, Limestone L deposited, Ash V2 falls, Shale H2 deposited, Layers tilted, Fault F moves, Dike D intrudes, Surface E erodes, Gravel G deposited. Other groups write their own.
4. Solve the case yourself first (the key is below) and decide how you will handle the intentional ambiguity between tilting and faulting; the strongest answer is that it cannot be ordered from these cards.

Investigation design

Independent variable	The set of evidence available: Round 1 (layer and fossil cards 1 to 7) versus Round 1 plus Round 2 (structural and dating cards 8 to 12)
Dependent variable	The number of events the group can place in the sequence with a rule and a card for each, and the number of layers given an age bracket
Controlled	Same cross section and card wording for every group; Every placement must cite a rule and a card; Same rule reference strip and same timeline format
Trials	One case per group; the class compares final sequences and the pairs marked as unorderable.
Comparison	How many events are placed after Round 1 (typically seven, with tilting floating) versus after Round 2 (eleven, with one unorderable pair).

Student procedure

1. Read the scenario on the recording sheet and study the two diagrams: the stack of layers from top to bottom, and the three features that cut across it. Agree on what each label refers to before opening any cards.
2. Round 1: open the Round 1 envelope (cards 1 to 7). The Card reader reads each card aloud. For each layer card, the Sequencer places a sticky note on the timeline strip and the Rule checker names the rule that justifies its position. Decide whether the stack could be upside down, and cite the card that settles it.
3. Record the Round 1 sequence on the recording sheet, one row per event, with the rule and the card numbers. Card 7 describes tilting; place it, and write down what you know about when tilting happened so far.
4. Round 2: open the Round 2 envelope (cards 8 to 12). Read each card aloud. Slot the fault, the dike, the erosion surface and the gravel into the sequence. For every placement, the Rule checker must state what the feature cuts and what it does not cut, and the Sequencer may not move a note without a card being cited.
5. Check for any pair of adjacent events whose order no card can prove. Mark that pair with a question mark on the timeline and record it on the sheet. Do not guess an order for it.
6. Fill in the age-bracket table using the three dated igneous features (cards 3, 5 and 9). For each layer or event, write the age it must be older than, the age it must be younger than, and the reasoning. Use 'unknown' when the evidence gives no bound.
7. Use card 12 to correlate: decide what the distant quarry's shale can be matched to in your quarry and how confident the match is.
8. Write the final sequence, oldest to youngest, on the recording sheet with the rule and card numbers for every step, then answer the analysis questions individually.
9. Compare your sequence with one other group's. Where you differ, each group reads the card it relied on aloud, and the class decides which reading is justified.

Expected observations

- After Round 1 every group places the six layers in order and most note that tilting came after H2, but they cannot place the tilting precisely.
- After Round 2 groups place the fault, dike, erosion surface and gravel; the most common error is placing the dike before the fault because it 'goes through everything', which card 9's unshifted crossing corrects.
- Most groups bracket limestone L correctly between 140 and 150 million years; some give H1 an upper bound of 150 but invent a lower bound, which the cards do not supply.
- Groups split on the tilting-versus-faulting order; the strongest groups mark it uncertain rather than guessing.

Likely difficulties

- Students read 'the dike reaches the bottom' as evidence of age; redirect them to what it cuts.
- Students bracket shale H2 as 'younger than 140' and forget that the dike, dated 90 million years, cuts it and so gives it a lower bound.
- The word 'bracket' is new; model it with the ash beds as the two ends of a bracket around the limestone.
- Some groups want to order tilting and faulting anyway; require a card for every placement and let the question-mark stand.
- The half-life fraction in q6 is not a whole number of half-lives; students may try to force it to one. The point is that 90 is a small fraction of 704, so most of the uranium-235 remains.

Structured debrief

1. Build the class sequence on the board from group answers: S, H1, V1, L, V2, H2 by superposition (card 1 rules out an overturned stack); tilting after H2 by original horizontality (card 7); fault F after H2 (card 8); dike D after the tilting because it is not tilted and after the fault because it is not offset (card 9); surface E after the dike (card 10); gravel G last (card 11).
2. Ask which pair could not be ordered. Tilting and faulting both come after H2 and before the dike, but no card says whether the fault cuts tilted layers or the fault itself was tilted. Ask what observation would settle it: a fault plane that is itself tilted by 20 degrees would mean faulting came first; a vertical fault cutting the tilted beds cleanly would suggest tilting came first, though even that is not airtight.
3. Walk the age brackets: L is between 140 and 150 million years by superposition between two dated ash beds; S and H1 are older than 150 million with no lower bound from these cards; H2, the tilting and the fault are between 140 and 90 million; E and G are younger than 90 million. Stress that no sedimentary layer was dated directly.
4. Discuss card 12: the distant shale with Q and R, below a coral limestone, most likely matches H1 and is therefore older than about 150 million years and within the span of type Q. Confidence rises with a short-lived index fossil, more shared species, or a dated ash bed in the distant quarry.
5. Close on q9: the wall records a sea becoming land, but the evidence places the change only somewhere between H2 and G, a gap of unknown length that includes tilting, faulting, intrusion and erosion. That gap is missing time, and geologists have a word for the buried erosion surface, an unconformity.

Recording sheet: what students fill in

Lab 2 recording sheet: The quarry case file

A quarry company cut a wall 40 m long and 15 m high through a hillside. A geologist spent a day describing it and wrote twelve evidence cards. Your job is to turn her observations into a sequence of events, with a rule and a card number for every step, and to put years on as many layers as the evidence allows. This quarry is invented for teaching, but every rule you use is the real method.

The quarry wall, top to bottom

Gravel G: flat, loose river gravel on top of everything, resting on erosion surface E	top
Shale H2 (tilted 20 degrees, like every layer below)	
Ash V2: a 10 cm volcanic ash bed	
Limestone L: gray, with coral fossils	
Ash V1: a 20 cm volcanic ash bed	
Shale H1: dark, with many fossils	
Sandstone S: the lowest layer exposed, with ripple marks	bottom

Layers S through H2 are all tilted 20 degrees toward the east; gravel G is flat and sits on the flat erosion surface E. Simulated teaching cross section.

Read the stack from the bottom up. The six tilted layers are drawn in their true order; surface E lies between H2 and G, and it, the tilt and the other cutting features are described on the cards and in the next figure.

Features that cut across the quarry wall

Fault F

A steep break running from the bottom of the wall up to surface E. The six tilted layers on its west side sit 3 m higher than the same layers on its east side.

Dike D

A vertical sheet of dark igneous rock 1 m wide, running from the bottom of the wall up to surface E. It crosses all six tilted layers and crosses fault F.

Surface E

A flat erosion surface that cuts off the tilted tops of the six layers, the top of fault F and the top of dike D.

Gravel G

A flat bed of river gravel lying on surface E across the whole wall. Nothing cuts it.

Which feature cuts which is the key to Round 2. Simulated teaching cross section.

Evidence cards (Round 1: cards 1 to 7; Round 2: cards 8 to 12)

Card 1

Card 1. Sandstone S is the lowest layer exposed in the quarry. Its ripple marks have sharp crests that point upward, toward shale H1, the way ripples form on a sandy bottom.

Card 2

Card 2. Shale H1 lies directly on sandstone S. It contains many small spiral-shelled fossils of type Q and some flat, clam-like fossils of type R.

Card 3

Card 3. Ash V1 is a 20 cm bed of volcanic ash lying directly on shale H1. Zircon crystals from the ash gave a radiometric age of 150 million years, plus or minus 2 million.

Card 4

Card 4. Limestone L lies directly on ash V1. It contains fossil corals and type R fossils, but no type Q.

Card 5

Card 5. Ash V2 is a 10 cm bed of volcanic ash lying directly on limestone L. Its zircon crystals gave a radiometric age of 140 million years, plus or minus 2 million.

Card 6

Card 6. Shale H2 lies directly on ash V2. It contains type R fossils and a different spiral-shelled fossil, type T. Type T has never been found in the same layer as type Q anywhere in the world.

Card 7

Card 7. All six layers, from sandstone S up through shale H2, are tilted 20 degrees toward the east, and all by the same amount.

Card 8

Card 8. Fault F is a steep break through all six tilted layers. The layers on its west side sit 3 m higher than the matching layers on its east side. The fault stops at surface E.

Card 9

Card 9. Dike D is a vertical sheet of dark igneous rock 1 m wide. It cuts straight through all six tilted layers and is not tilted itself. Where it crosses fault F, the dike is continuous and not shifted. A mineral from the dike gave a radiometric age of 90 million years, plus or minus 1 million.

Card 10

Card 10. Surface E is a flat erosion surface. It cuts off the tilted tops of all six layers, the top of fault F and the top of dike D.

Card 11

Card 11. Gravel G is a flat bed of loose river gravel lying on surface E across the whole wall. It contains a bone of a land animal. Nothing cuts gravel G.

Card 12

Card 12. In a quarry 300 km away, a dark shale containing fossil types Q and R lies below a limestone containing corals. No ash bed has been found there.

Sequence of events (fill in during Round 1, revise in Round 2)

Step (1 = oldest)	Event	Rule used	Card number(s)	Certain or uncertain?
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				

Age brackets from the dated igneous features

Layer or event	Must be older than (million years)	Must be younger than (million years)	Reasoning and cards
Sandstone S			
Shale H1			
Limestone L			
Shale H2			
Tilting			
Fault F			
Dike D			
Surface E and gravel G			

- Which pair of events could your group not put in order from the cards? Explain why no card settles it.

Answer: Tilting and the movement of fault F. Both happened after shale H2 and before dike D, but no card says whether the fault cuts already-tilted layers or whether the fault itself was tilted along with them.

Why: The cards were written to leave this pair unordered; a group that forces an order has gone beyond the evidence.

- Names tilting and faulting
- Explains that no card gives a cutting relationship between them

- Which single card did the most work in Round 2, and what did it let you conclude?

Answer: Card 9. It places the dike after the tilting (the dike is vertical and not tilted) and after the fault (the dike is continuous where it crosses the fault), and it gives the 90-million-year date that bounds everything after shale H2.

Why: Card 10 is an acceptable alternative if the student explains that it ties the erosion surface to everything below it.

Also acceptable: Accept card 10 or card 8 with a correct explanation of what it allowed the group to conclude.

Analysis questions: answer key

3. Which layer was deposited first? Give the rule, and give the evidence from card 1 that shows the stack is not upside down.

Answer: Sandstone S, by superposition: it is the lowest layer in a stack that is not overturned. Card 1 shows the stack is right side up because the ripple crests point upward toward H1, the way ripples form on a sandy bottom.

Why: The ripple-mark evidence is the 'way-up' indicator mentioned in the slide 12 notes; superposition needs that assumption checked.

- Sandstone S
- Superposition
- Ripple crests pointing up as the way-up evidence

4. Explain how you placed dike D relative to the tilting and relative to fault F. Quote the specific observations from card 9 that each placement rests on.

Answer: Relative to tilting: card 9 says the dike is vertical and not tilted, while the layers it cuts are tilted 20 degrees. If the dike had been there before the tilting, it would have been tilted too, so the dike came after the tilting. Relative to the fault: card 9 says the dike is continuous and not shifted where it crosses fault F. A fault that moved after the dike formed would offset the dike, so the fault moved before the dike intruded. Both placements use cross-cutting relationships: the feature that is cut (or would have been affected) is the older one.

Why: Two separate arguments are needed, each tied to its observation; the 'would have been tilted too' step is the subtle one.

- Dike after tilting, using 'not tilted'
- Dike after fault, using 'not shifted at the crossing'
- Names cross-cutting relationships

5. What is the age bracket for limestone L? Write it as 'between ___ and ___ million years' and show how the two ash dates and superposition give it.

Answer: Between 140 and 150 million years. Ash V1 (150 million years) lies below L, so L is younger than 150 million; ash V2 (140 million years) lies above L, so L is older than 140 million. Superposition links the dated ash beds to the limestone between them.

Why: A bracket from two dated igneous layers; the uncertainties of plus or minus 2 million widen it slightly (roughly 138 to 152) and students may mention this.

Also acceptable: Accept 138 to 152 million years if the student applies the stated uncertainties.

6. Dike D is 90 million years old. The half-life of uranium-235 is about 704 million years. What fraction of one half-life has passed since the dike formed? Has more or less than half of the dike's uranium-235 decayed? Show your reasoning.

Answer: $90 \div 704 \approx 0.13$, so about one eighth of one half-life has passed. Far less than half has decayed: half decays only after a full 704 million years, so after 0.13 of a half-life most of the uranium-235 is still there (roughly 91 to 92 percent remains, about 8 to 9 percent decayed).

Why: Students do not need the exact percentage; the required reasoning is that a small fraction of a half-life means a small fraction decayed. The exact value is $1 - 0.5^{0.128} \approx 0.085$.

Also acceptable: Accept 'about 0.13 of a half-life, so much less than half decayed' without the percentage.

7. Fossil type Q is found only in shale H1; type R is found in H1, L and H2. Which is the better index fossil, and why? What does card 6 tell you about type T compared with type Q?

Answer: Type Q is the better index fossil: it occurs in only one layer, so finding it pins a layer to that span of time, while type R occurs in three layers spanning more than 10 million years and narrows the age much less. Card 6 says type T is never found with type Q, which means the two species lived at different times; T appears above V2, so T lived later than Q, and the two together give a sequence that fossil succession says should hold everywhere.

Why: Short-lived versus long-lived species, and non-overlap as evidence of different time spans.

- Q is better because it occurs in one layer only
- R spans several layers so narrows less
- T lived later than Q and the two never overlap

8. Use card 12. Which layer in your quarry does the distant shale most likely match, and what can you say about its age in years? How confident are you, and what would raise your confidence?

Answer: The distant shale most likely matches shale H1: it holds the same two fossil types, Q and R, and sits below a coral limestone, the same position as H1 below L. By fossil succession and the bracket in this quarry, it formed within the span of type Q, which here is older than about 150 million years. Confidence is moderate: Q may have lived for several million years, and only two fossil types are shared. Confidence would rise with a dated ash bed in the distant quarry, more shared species, or a known short lifespan for type Q.

Why: Correlation by fossils gives 'about the same age', bounded by the species' span; the honest confidence statement is part of full credit.

- Matches to H1 with the fossil and position reasons
- Age: within type Q's span, older than about 150 million years
- States limits of confidence and what would improve it

9. The lower layers hold corals and sea-floor fossils; gravel G holds a land animal's bone. What change does the wall record, and where in your sequence can you place it? What can the evidence not tell you about how long the change took?

Answer: The wall records a change from a sea floor (corals and marine fossils in L and the shales) to dry land with a river (gravel with a land animal's bone). The change happened somewhere after shale H2 and before gravel G, during the stretch that also includes tilting, faulting, the dike and the erosion of surface E. The evidence cannot say how long that stretch lasted or how long the change took; between 140 and 90 million years the only fixed point is the dike, and after 90 million years there is no date at all. The erosion surface is missing time.

Why: Students should place the change in the sequence and name the limits on timing.

- Sea to land change identified from the fossils
- Placed between H2 and G
- States that the duration and exact timing are unknown

- 10.** A classmate argues that dike D must be the oldest feature because it reaches the bottom of the quarry wall. Write a two-sentence response that uses the correct rule and cites two cards.

Answer: Reaching the bottom of the wall shows where the dike is, not when it formed; by cross-cutting relationships a dike is younger than every layer it cuts, so dike D is younger than all six layers (card 9). It is also younger than fault F, because card 9 says the dike is unbroken where it crosses the fault, and older only than surface E and gravel G (cards 10 and 11).

Why: The response must correct the depth-equals-age error with the rule and cite two cards.

- States the cross-cutting rule
- Cites two of cards 9, 10 and 11
- Rejects depth as evidence of age

Individual evidence of learning

Each student submits the completed sequence table with a rule and card for every step, the age-bracket table, and individual answers to q1 through q10. The sequence table and q4 are the primary evidence for constructing an explanation from strata evidence; q5 and q8 are the evidence for bracketing and correlation.

Assessment criteria

Criterion	Proficient looks like
Sequence with justification	All eleven events in a defensible order, each with the correct rule and the card that supports it; the tilting-faulting pair is marked uncertain rather than guessed.
Cross-cutting reasoning	Places the dike after the tilting (not tilted) and after the fault (not offset), and the erosion surface after the dike, citing card 9 and card 10.
Age bracketing	Limestone L bracketed between 140 and 150 million years; H2, tilting and fault bracketed between 140 and 90 million; S and H1 older than 150 with no invented lower bound; E and G younger than 90.
Fossil reasoning	Identifies Q as the better index fossil because it occurs in one layer, explains that T and Q never co-occur because they lived at different times, and matches the distant shale to H1 with an honest confidence statement.

Accessibility adaptations

- Provide the pre-written event sticky notes so the work is ordering, not writing, for students who need it.
- Offer the cards in large print and let the Card reader role rotate so every student hears every card twice.
- Allow the sequence to be submitted as a photographed timeline strip with the recorder's table, and accept spoken answers for q4 and q9.
- Provide a multilingual card for tilt, offset, cut, bracket and ash, and a worked example of bracketing with two made-up dates before the lab.

Low-cost alternative

Write the twelve cards on index cards by hand and draw the two diagrams on the board; the lab needs no printing at all beyond the recording sheet, which can be copied by students into notebooks.

Model limitations

The quarry is invented and simplified: real walls hold more layers, fossils are rarely so tidy, radiometric dates come from careful mineral separation rather than a single sentence, and the same-amount tilting of all six layers is assumed rather than measured. The ambiguity between tilting and faulting is deliberate and is a real limitation of such evidence. The card-based format has been designed from the textbook's rules and standard geologic practice but has not been trialed with a class; adjust the number of cards per round if groups finish Round 1 too quickly.

Teacher notes

The full solution: S, H1, V1, L, V2, H2 (superposition; card 1 confirms way-up), then tilting and fault F in unknown order (cards 7 and 8), then dike D (card 9), then surface E (card 10), then gravel G (card 11). Age brackets: S and H1 older than 150; L between 140 and 150; H2, tilting and fault between 140 and 90; dike 90; E and G younger than 90, all in millions of years. Give full credit for marking tilting and faulting uncertain and partial credit for a forced order with a stated reason. If a group asks whether the sandstone's own grains could be dated, say that would date the older rock the sand came from, giving only a maximum age.