

Mars geology and field science

This course develops a capability that was still missing from the core curriculum. It starts from concepts and units, builds the necessary calculations, then connects each method to real Mars engineering decisions.

Before starting — Prerequisites: modules 00 to 22 as relevant. Every important symbol is defined at first use.

Mastery objectives

- explain quantities, units and assumptions
- repeat at least one calculation by hand
- identify uncertainty, limits and failure modes
- turn the result into a decision for a Mars architecture

1. Read a landscape as a history

Field geology studies relationships: what lies above, below, cuts, displaces or erodes something else. A sample without context gives composition; a sample tied to its unit and landscape gives history.

Human crews can move faster than rovers, but speed becomes a scientific risk if context is not recorded.

Engineering reflex. Identify what is measured, assumed and calculated, then state what would change the decision.

2. Stratigraphy before absolute age

Superposition usually places younger layers above older ones in an undisturbed sequence. Cross-cutting relations, faults, intrusions and craters build a relative timeline.

Absolute ages require a dating method and assumptions about geochemical closure.

3. Volcanism, impacts, water and wind

Mars preserves volcanic terrains, craters, valleys and sediments. Each process leaves different geometries and textures.

Earth analogs help recognise processes but Mars has different gravity, pressure and climate history.

4. Mapping and traverses

A scientific traverse connects objectives, stops, time, safety, return margin and sample priorities. Crews prepare hypotheses before leaving and update them in the field.

NASA trains astronauts in geology because human observation can reformulate a question quickly, but every change must be documented.

5. Sample chain of custody

A valuable sample stays linked to location, orientation, geologic unit, pre-sampling imagery and storage history.

A Mars base must separate scientific, industrial and biological-control samples because each requires different contamination rules.

6. Observe before sampling: context, contacts and geometry

A sample without context loses much of its scientific value. Before breaking rock, the crew describes the outcrop, photographs contacts between layers, records structural orientation and ties the point to the traverse path. This discipline helps distinguish in-place material from transported fragments and reconstruct the sequence of geological events. Field operations therefore budget time to observe and document, not merely to fill containers.

7. Design a traverse as both a science problem and a safe-return problem

The optimum route is not necessarily the shortest. A field traverse combines science value, slope, soil bearing, energy, communications, EVA time, return margin and retreat points. Every stop should have a reason: test a hypothesis, inspect a contact, sample a different unit or investigate an orbital anomaly. Good planning also defines which stops will be dropped first if battery state, weather or crew health deteriorates.

8. Chain of custody: preserve the history of the sample

After collection, science depends on traceability. Identifier, time, position, tool, operator, photograph, container and every transfer should remain linked to the sample. Contamination blanks and witnesses help identify material introduced by gloves, airlocks or the laboratory. On Mars, that chain protects ordinary geological interpretation and is even more important for organics or biosignature work, where a small contamination event could produce a disproportionate conclusion.

Field case: the most spectacular rock is not necessarily the best sample

A striking rock found out of context can be less useful than an ordinary sample collected from a bed whose position is known. Geology studies relationships: what lies above, below, cross-cuts, alters or transports material. Before sampling, the team images the site, records stratigraphic unit and assigns a stable identifier. If the sample is later subdivided, every subsample inherits that lineage. This chain connects a laboratory measurement back to geological history.

9. Worked example step by step

A worked traverse example combines route distance, travel speed, seven science stops and an explicit operational margin. The complete arithmetic is developed in the “Protected science time inside an EVA traverse” mini-lesson below, where each unit conversion, reserve and credibility check is shown line by line rather than compressed into prose.

10. Progressive exercise

Plan an 8 km traverse with four mandatory and three optional stations. Define travel speed, observation time per station, a 30% return margin and an explicit rule for dropping optional objectives.

11. Reasoned solution

A second traverse variant uses a higher driving speed but longer science stations, plus navigation margin and a protected reserve. The learner should apply the same time-budget method and determine whether the six-hour window closes; the point is to make the protected-return decision from a reproducible budget, not from intuition.

12. Validation mini-project

Create the field operations book for a Mars geology traverse: orbital assumptions, route map, stations, expected observations, photo protocol, chain of custody, abort criteria and the data package required by the laboratory.

Advanced field geology laboratory — preserve context, test hypotheses, protect the sample story

This field-science extension links geological observation to sampling logic, context preservation, chain of custody, uncertainty and mission decisions so evidence remains scientifically defensible after the traverse.

Build competing hypotheses before the traverse

A field team should not leave the habitat with a single preferred story. Orbital images, topography and prior rover observations can support several interpretations. Write at least two competing hypotheses and identify observations that would discriminate between them. This reduces confirmation bias and helps the team decide which contacts, layers or clasts deserve limited EVA time.

Record context before touching the target

The scientific value of a sample depends on where it came from, its orientation, relationship to surrounding units and evidence of transport or alteration. Photograph the outcrop at several scales, record position and geometry, describe nearby contacts and note uncertainty before extraction. Once a sample is removed, part of that context can never be recreated.

Design the traverse with a protected return margin

Scientific optimization sits inside an operational envelope. Route length, slope, terrain trafficability, communication coverage, suit resources, weather and medical constraints all affect the usable field window. Define drop criteria for lower-priority stops before departure. A traverse that collects fewer samples but returns with documented context and reserve is superior to one that exhausts margin chasing an attractive final target.

Keep chain of custody continuous

Assign a stable identifier at collection and carry it through container, transfer, airlock, laboratory and subsampling. Record who handled the material, what tools contacted it and which storage conditions changed. Blanks and witness materials help identify contamination introduced by the collection system. Chain of custody protects ordinary geologic interpretation and becomes even more important when organic chemistry or possible biosignatures are involved.

Separate observation, inference and conclusion

Field notes should distinguish what was directly observed from what is inferred. 'Fine-grained red layer 12 cm thick' is an observation; 'lake deposit' is an interpretation that requires supporting evidence. This separation makes later reinterpretation possible when laboratory results or new imagery contradict the initial field hypothesis.

Progressive mastery drills — eight linked checks

▼ Drill 1 — Relative chronology

Order layers and cross-cutting features before assigning an absolute age. Explain which relation is directly observed and which is inferred.

Expected reasoning. State the evidence, the assumption, the uncertainty and the operational consequence. A label or definition alone is not a complete answer.

▼ Drill 2 — Rock, mineral and texture description

Describe grain size, fabric, colour and visible minerals before naming a genetic process.
List at least one alternative interpretation.

Expected reasoning. State the evidence, the assumption, the uncertainty and the operational consequence. A label or definition alone is not a complete answer.

▼ Drill 3 — Stratigraphic relation

Use superposition, contacts and cross-cutting relations to construct a relative event sequence.

Expected reasoning. State the evidence, the assumption, the uncertainty and the operational consequence. A label or definition alone is not a complete answer.

▼ Drill 4 — Aqueous alteration evidence

Separate morphology, mineralogy and texture. State what additional measurement would strengthen or weaken the water-related interpretation.

Expected reasoning. State the evidence, the assumption, the uncertainty and the operational consequence. A label or definition alone is not a complete answer.

▼ Drill 5 — Mapping and scale

Show how a feature visible from orbit is connected to an EVA-scale observation without pretending the scales are interchangeable.

Expected reasoning. State the evidence, the assumption, the uncertainty and the operational consequence. A label or definition alone is not a complete answer.

▼ Drill 6 — Field notebook metadata

Specify time, position, orientation, instrument, operator and environmental state needed to make the observation reusable.

Expected reasoning. State the evidence, the assumption, the uncertainty and the operational consequence. A label or definition alone is not a complete answer.

▼ Drill 7 — Sampling representativeness

Explain how several samples reduce the risk of treating an unusual clast as representative of a whole unit.

Expected reasoning. State the evidence, the assumption, the uncertainty and the operational consequence. A label or definition alone is not a complete answer.

▼ Drill 8 — Geology for resources and siting

Connect one geologic observation to both a resource opportunity and an engineering hazard.

Expected reasoning. State the evidence, the assumption, the uncertainty and the operational consequence. A label or definition alone is not a complete answer.

▼ Integrated exercise — Eight-step field validation drill

For a candidate sampling site, produce eight short records: landscape history, rock/mineral description, relative-age relationship, evidence for or against aqueous alteration, map scale and position, field metadata, sampling representativeness, and relevance to resources or site engineering. For each record, state one uncertainty and one observation that would reduce it.

Reasoned solution. A strong submission keeps the eight records separate, avoids turning interpretation into observation, and links every proposed sample to a question. The final sampling plan should show why the selected set is more informative than simply collecting

the most visually distinctive rocks.

Primary-source bridge for this extension. [Official source 1](#) [Official source 2](#) [Official source 3](#). These links are evidence anchors already present in the French reference module; values and limits must still be checked against the source version applicable to the mission.

Primary sources and bridges

- [NASA Artemis geology training](#)
- [NASA NTRS — Geology and Field Training](#)

- [NASA NTRS — astronaut geoscience field training](#)
- [NASA — Planetary analogs](#)

First Man field geology dossier — reconstruct history without destroying the evidence

Field geology on Mars is a chain of reasoning under severe operational constraints. The learner must be able to move from orbital context to outcrop, from observation to competing hypotheses, from a rock in place to a traceable sample, and from an interesting target to a traverse that still protects the crew. This dossier makes that chain explicit and gives each decision an evidence requirement.

Read the landscape before choosing a rock

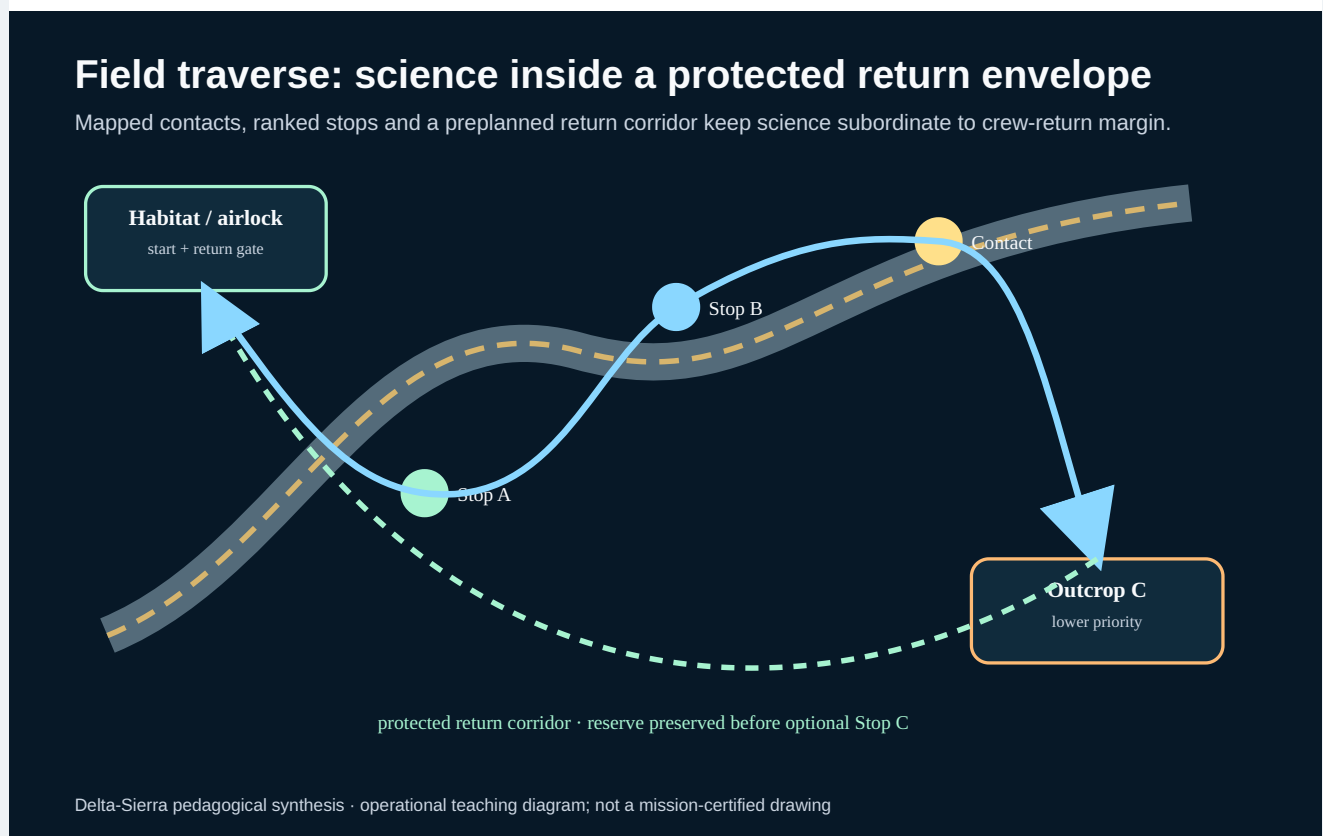
Geology begins at multiple scales. Orbital images suggest units, contacts, slopes and landforms; rover or EVA observations reveal grain size, texture, fracture, bedding and alteration that cannot be inferred reliably from orbit alone. The [NASA — planetary analogs](#) shows why Earth analog sites remain useful for learning how scale, access and incomplete exposure shape interpretation. The key discipline is to record what each scale actually resolves instead of allowing a dramatic orbital feature to dictate the field conclusion.

Before departure, build at least two plausible geologic histories. For example, a layered unit may represent sedimentary deposition, volcanic material, impact-related deposits or later reworking. Each hypothesis should predict an observation that could weaken it. The traverse is then designed to seek discriminating evidence rather than to confirm the story the team already prefers.

Map contacts, orientation and context before sampling

The field team should preserve spatial relationships before touching the target. Record the outcrop face, contact geometry, layer thickness, clast relation, fracture orientation, local topography and uncertainty. Training described in [NASA — Artemis geology field training](#) illustrates the operational importance of astronaut field practice: observation, communication and sample decisions are skills, not automatic consequences of scientific education.

A sample without context is often much less valuable than a less spectacular sample tied to a well-documented unit. Use overview, mid-range and close imagery; include a scale; identify north or a local reference; and record whether the material is in place, transported, fractured, weathered or partly buried. If orientation matters, mark it before extraction.



Mapped contacts, ranked stops and a protected return route connect geologic objectives to EVA margin. Pedagogical synthesis by Delta-Sierra from the primary sources cited at the point of use; not a mission-certified drawing.

Build a relative chronology before assigning an absolute age

Superposition, cross-cutting relations, inclusions and contact geometry let the team reconstruct an event order without pretending to know absolute dates. A fracture cutting a layer is younger than that layer; a clast enclosed in a later deposit is older than the enclosing material. These principles sound elementary, but they become difficult when exposure is incomplete or when later alteration overprints earlier textures.

Write the chronology as a sequence with confidence levels: observed relation, inferred event and competing explanation. That structure prevents a later laboratory result from becoming an apparent contradiction when it actually changes only one inference. Absolute dating, where available, should attach to this relational framework rather than replace it.

Design a traverse as a science optimization inside a safety envelope

The [NASA NTRS — planetary field geology training](#) is relevant because planetary field work is taught as an integrated activity: route, observation, documentation, sampling and communication compete for time. A Mars traverse must also protect return time, suit consumables, communications, thermal constraints, medical state and contingency. Rank stops before departure and define which ones are dropped first if the timeline degrades.

Do not spend reserve twice. A rover energy reserve that protects the return path cannot simultaneously be treated as spare energy for an optional detour. Likewise, an EVA time reserve is not “unused science time.” The first atlas figure below separates mandatory return geometry from optional targets so the visual plan itself exposes this discipline.

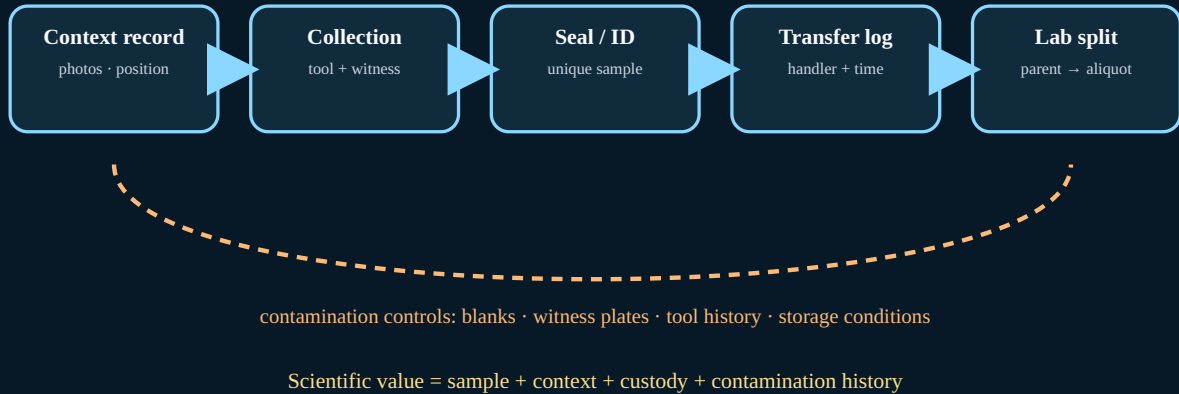
Treat chain of custody as part of the scientific measurement

A stable sample identifier begins at collection and survives every container change, airlock transfer, laboratory handoff and subsample. The [NASA NTRS — science operations / field methods](#) supports the broader lesson that operations and science quality are coupled. Record handler, time, tool, container, storage condition and any event that could alter the sample. A later analyst should be able to reconstruct what happened without relying on someone’s memory.

Contamination control is especially important when the question involves organics, volatiles or possible biosignatures. Field blanks, witness materials, tool histories and clean/dirty zoning do not prove that a signal is indigenous, but they make contamination hypotheses testable. “We were careful” is not a chain of evidence.

Sample chain of custody and contamination control

The sample identifier persists from outcrop context through sealing, transfer and laboratory subdivision.



Delta-Sierra pedagogical synthesis · operational teaching diagram; not a mission-certified drawing

Sample identity, context, handling and contamination controls remain linked from outcrop to laboratory split. Pedagogical synthesis by Delta-Sierra from the primary sources cited at the point of use; not a mission-certified drawing.

Separate observation, inference, hypothesis and conclusion

Use four labels in notes and debriefs. Observation: what was directly seen or measured.

Inference: what process might explain it. Hypothesis: a broader testable story connecting several observations. Conclusion: the current best-supported interpretation after comparison with alternatives. This vocabulary is an anti-bias tool.

For example, “fine-grained layer, 12 cm thick, laterally continuous for 8 m” is observation.

“Deposited in standing water” is an inference that requires texture, mineralogy, geometry and context. A professional report keeps those levels distinct so new data can revise the interpretation without rewriting the observations.

Use instruments to answer a field question, not to decorate the traverse

Every instrument has a spatial resolution, detection limit, calibration state and environmental sensitivity. The team should be able to say what decision the measurement changes. If a spectrometer result cannot distinguish the two hypotheses under consideration, it may be scientifically interesting but not the best use of a constrained EVA minute.

The correct sequence is question → required observation → instrument capability → acquisition protocol → quality check → interpretation. This sequence also exposes when the field team needs a repeat measurement, a blank, a reference target or a laboratory follow-up before drawing a conclusion.

Board scenario — a spectacular vein competes with a boring contact

A bright vein appears 450 m beyond the planned final stop. It could record fluid activity, but reaching it consumes most of the optional science time and pushes the return path into degraded-light conditions. The team already has a lower-risk contact where two units meet, which directly tests the day's competing stratigraphic hypotheses.

A defensible board decision does not ask which rock looks more exciting. It asks which observation has the highest discriminating value inside the protected traverse. The vein may become a future target with a dedicated route. Today, the contact can be the higher-value sample because it closes a specific question without borrowing the return reserve.

Operational review drills — explain the evidence, not only the answer

1. **Hypothesis drill.** Write two competing origins for a layered outcrop and one observation that would discriminate between them.
2. **Context drill.** List the minimum metadata needed before removing an oriented sample.
3. **Traverse drill.** Remove one optional stop after a 35-minute delay without using protected return time.
4. **Custody drill.** Design a sample identifier and handoff record that survives three operators and two laboratory splits.
5. **Contamination drill.** Choose one blank and one witness control for an organic-sensitive sample.
6. **Chronology drill.** Order four events using superposition and cross-cutting evidence, then state one ambiguity.

Qualification notebook — five field decisions that can invalidate a sample campaign

A field team is qualified by the quality of its decisions when evidence is incomplete. The following cases are deliberately uncomfortable: each one forces the learner to protect context, crew margin or contamination control instead of maximizing the number of collected rocks.

Review-board ledger

- Question being tested
- Observation needed to discriminate hypotheses
- Required context before sampling
- Contamination control
- Protected return / contingency
- Sample custody status
- Uncertainty that remains after return

▼ Case 1 — the unit boundary is farther than the map predicted

Situation. Orbital mapping placed a contact 600 m from the airlock, but the crew reaches the predicted coordinate and finds only float and dust cover. A possible bedrock exposure lies another 350 m downslope. The EVA already consumed 55 minutes more than planned because of trafficability. Decide whether to continue, what evidence to collect at the original point and what should be written into the traverse record.

Reasoned disposition. Do not convert map uncertainty into an automatic extension. First document the mismatch: position, imagery, surface material, slope and why the expected contact was not confirmed. Recompute protected science time and return margin with the delay included. If the extra 350 m would consume contingency or erode suit/rover reserve, HOLD the extension and preserve the new exposure as a future target. The scientifically honest outcome can be “contact not located at predicted position.” That is useful evidence because it updates the map without inventing a field confirmation.

▼ Case 2 — a sample breaks before orientation is recorded

Situation. A layered block is removed successfully but fractures into three pieces before its orientation arrow is photographed. The operator remembers approximately which face was up. Another crew member has a wide-angle image of the outcrop but no close image of the

extraction point. Can the sample still be used, and how should the uncertainty be recorded?

Reasoned disposition. The sample remains useful for questions that do not require exact orientation, but its orientation history is degraded. Preserve all fragments under the same parent identifier, record the break event immediately, link the wide-angle image and mark orientation as uncertain rather than reconstructed from memory. Do not create a precise arrow later because a crew member is confident. If structural interpretation requires orientation, treat that question as not closed and schedule a replacement sample or in-situ measurement.

▼ Case 3 — organics appear only in one tool path

Situation. Two adjacent samples are geologically similar. The sample collected with Tool A shows an organic signal; the one collected with Tool B does not. A witness plate associated with Tool A also contains a related compound. The attractive interpretation is indigenous organics. What is the correct next step?

Reasoned disposition. The witness result makes contamination a live hypothesis that must be tested before any indigenous interpretation is promoted. Quarantine the affected analytical branch, preserve raw spectra and tool history, compare blanks, inspect cleaning records and seek an independently collected sample using a separate clean tool path. The scientific value of the first signal is not zero; it becomes evidence about contamination control until the competing contamination explanation is reduced.

▼ Case 4 — the visually boring sample has the better chain of evidence

Situation. Sample A is spectacular but was collected from loose float with uncertain provenance. Sample B is visually ordinary but comes from an in-place contact with orientation, stratigraphic context and complete custody. Cargo allocation allows only one sample to receive the highest-priority analytical slot.

Reasoned disposition. Prefer the sample that best answers the stated question. If the campaign question concerns the age or alteration of the mapped unit, Sample B usually has higher evidentiary value because its relationship to the unit is defensible. Sample A may

still merit screening for unusual mineralogy, but visual novelty is not a substitute for provenance. State the decision criterion before choosing so the team does not reverse-engineer a rationale after seeing the rock.

▼ Case 5 — return margin and science ambition diverge

Situation. The crew has enough suit consumables for the nominal plan, but a degraded rover wheel increases the conservative return time by 35 minutes. The final target could resolve the leading geologic hypothesis and needs 40 minutes on site. The team can physically reach it by consuming most of the contingency.

Reasoned disposition. Do not redefine contingency as science time because the target is valuable. Update the traverse clock using the degraded return estimate, then protect the agreed contingency and ingress reserve. The final target is deferred unless another lower-priority activity can be removed while preserving the protected timeline. Record why the target matters and which future traverse could reach it efficiently. A high-value science objective does not change the meaning of a safety reserve.

Protected science time inside an EVA traverse

$$T_{\text{science}} = T_{\text{EVA}} - T_{\text{out}} - T_{\text{return}} - T_{\text{contingency}} - T_{\text{ingress}}$$

1 – Concrete question

How much field time remains for observation and sampling after the return path, contingency reserve and ingress are protected?

2 – Intuition without symbols

Start with the approved EVA duration and subtract time that is already committed to reaching the field site, returning safely, preserving contingency and completing ingress. Only the remainder is available for optional science.

3 – Quantities first

T_{EVA} is approved EVA duration; T_{out} outbound travel; T_{return} conservative return travel; $T_{\text{contingency}}$ protected reserve; T_{ingress} time reserved for airlock approach, cleanup and ingress; T_{science} is the remaining science window.

4 – Formula

$$T_{\text{science}} = T_{\text{EVA}} - T_{\text{out}} - T_{\text{return}} - T_{\text{contingency}} - T_{\text{ingress}}$$

5 – Read aloud

“T science equals T EVA minus T out minus T return minus T contingency minus T ingress.”

6 – Symbols

T denotes time. Subscripts identify the part of the timeline. Every term must use the same time unit.

7 – Pronunciation

T is read “tee”; EVA is read as the letters E-V-A.

8 – Units

hours – hours – hours – hours – hours = hours.

9 – Convention

Use conservative return time, not the faster outbound time, when terrain, fatigue or sample load can slow the crew. A negative result means the traverse is infeasible as planned.

10 – Why this operation

Each subtracted term is time already committed to crew survival or the basic traverse. Science uses only the remainder because optional objectives must not borrow the protected return reserve.

11 – Assumptions

The simplified timeline treats the durations as additive and assumes no overlapping task. Real plans also include suit consumables, communications, medical state, weather, trafficability and location-specific constraints.

12 – Unit check

Every term is a duration in hours, so the result is a duration in hours.

13 – Numerical case

Approved EVA window $T_{\text{EVA}} = 6.5$ h.

Outbound travel $T_{\text{out}} = 1.1$ h.

Conservative return $T_{\text{return}} = 1.2$ h.

Protected contingency $T_{\text{contingency}} = 0.8$ h.

Ingress and cleanup $T_{\text{ingress}} = 0.4$ h.

Committed non-science time = $1.1 + 1.2 + 0.8 + 0.4 = 3.5$ h.

$T_{\text{science}} = 6.5 - 3.5 = 3.0$ h.

14 – Why each operation

Add the committed durations to see how much of the EVA is already spoken for, then subtract that total from the approved EVA window. Keeping return and contingency separate prevents science from silently consuming emergency margin.

15 – Algebra check

For a required science window, the maximum allowable outbound-plus-return travel is $T_{\text{EVA}} - T_{\text{science}} - T_{\text{contingency}} - T_{\text{ingress}}$.

16 – Mental estimate

A 6.5-hour EVA with roughly 3.5 hours committed should leave about three hours, so 3.0 h is plausible.

17 – Interpretation

The team has a three-hour science window under the stated timeline, before other consumable or weather constraints are considered.

18 – What it does not prove

It does not prove the route is safe, the suit has enough consumables, communications work, the samples are worth collecting or the crew can physically maintain the assumed pace.

19 – Sensitivity or limit case

If return time rises from 1.2 to 1.6 h because of fatigue or a loaded rover, science time falls to 2.6 h. If the result reaches zero, optional stops must be removed rather than consuming protected reserve.

20 – Practice

Guided exercise. For a 7.0 h EVA with 1.3 h outbound, 1.4 h return, 0.9 h contingency and 0.4 h ingress, calculate the science window.

Detailed guided correction.

1. Committed time = $1.3 + 1.4 + 0.9 + 0.4 = 4.0$ h.

2. $T_{\text{science}} = 7.0 - 4.0 = 3.0$ h.

3. The three-hour result is only a time budget; the traverse still needs consumable, weather and medical checks.

Autonomous exercise. A traverse has a 6.0 h EVA limit, 0.9 h outbound, 1.1 h expected return, 0.8 h contingency and 0.4 h ingress. A new stop needs 1.2 h science time, but degraded terrain could add 0.7 h to return. Decide whether the stop remains inside the protected timeline.

▼ Autonomous correction – open after attempting the exercise

One defensible worked solution.

1. Nominal science time = $6.0 - 0.9 - 1.1 - 0.8 - 0.4 = 2.8$ h.
2. Degraded return = $1.1 + 0.7 = 1.8$ h.
3. Degraded science time = $6.0 - 0.9 - 1.8 - 0.8 - 0.4 = 2.1$ h.
4. The 1.2 h stop fits the time budget with 0.9 h remaining, but the decision still requires suit, weather, communications and terrain evidence.

21 – Mission decision

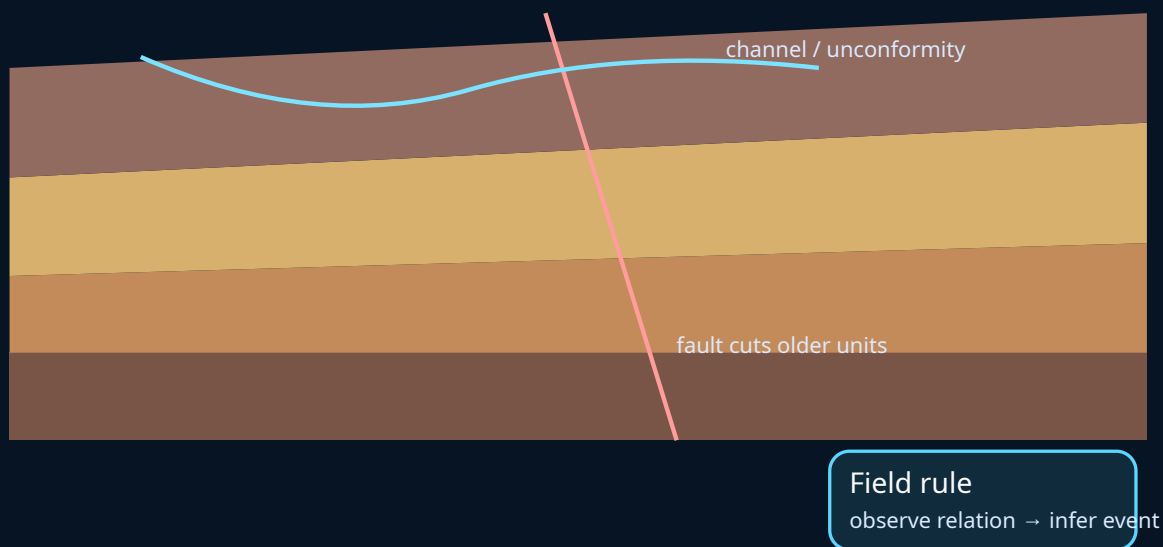
Approve optional field stops only after protected return and contingency time remain explicit. Drop lower-priority science before consuming emergency margin.

Closure rule. The learner should be able to reconstruct the model, challenge its assumptions, preserve the relevant safety or quality margin and state what additional evidence a real mission would require. This course does not confer operational certification.

defensible sample campaign

The field dossier established safe traverse time and sample traceability. The qualification layer extends that work into the reasoning a crew needs when the outcrop is incomplete, observations conflict, sampling capacity is limited and later laboratory interpretation depends on what the team chose to record in the field.

Stratigraphic cross-section and event order



Layered terrain, an erosional channel and a cross-cutting fault show how relative-age relationships are reconstructed. Pedagogical synthesis by Delta-Sierra from the primary sources cited in this dossier; not a mission-certified drawing.

Reconstruct history from relationships before naming an environment

Primary-source bridge: [NASA NTRS — planetary field geology training](#).

Geology begins with relative relationships. A layer overlain by another layer, a fracture cutting both, a vein filling that fracture and a younger surface deposit together define an event order even before any absolute age is known. The team should write that sequence in observation language first, then attach interpretations with confidence levels.

This discipline matters on Mars because many outcrops are partial. Wind erosion, dust, impact gardening and later alteration can remove the clean textbook contacts. A defensible field note therefore distinguishes what is physically seen from the process used to explain it.

Texture and mineralogy answer different questions

Texture records grain size, shape, sorting, fabric, vesicles, crystals, clasts and relationships between components. Mineralogy identifies the phases present. Either one without the other can mislead. A sulfate-bearing unit may record several environmental histories depending on its texture, context and later alteration.

The field team therefore avoids turning one mineral detection into an environmental headline. It records the scale of observation, instrument, detection limit, surface preparation and whether the measurement represents a coating, vein, clast or host rock.

Map contacts at multiple scales

Orbital mapping, rover-scale mapping and hand-sample mapping do not simply duplicate each other. Orbital data define regional units and accessible targets; traverse observations resolve contacts and structures; close observations test grain-scale hypotheses. The crew should be able to trace how a question moves across those scales.

A useful map is not just a route line. It records unit boundaries, uncertain contacts, structural orientation, hazards, sample sites, rejected sites and the observations that caused the route to change. That audit trail makes later reinterpretation possible.

Sampling should test hypotheses, not maximise container count

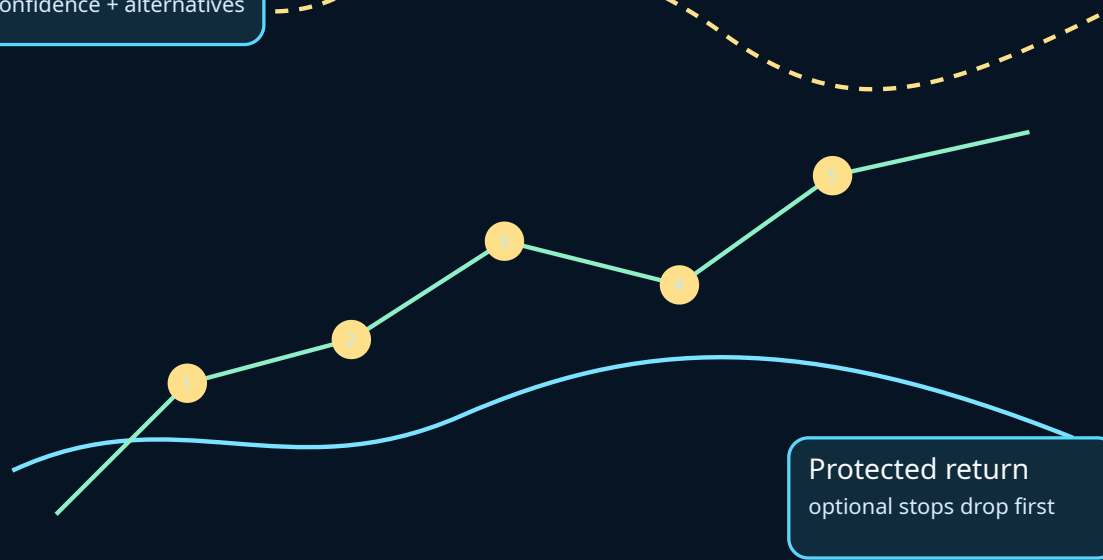
Primary-source bridge: [NASA — planetary analogs](#).

A sample campaign is strongest when each specimen has a question. Replicates test local variability; samples across a contact test change; blanks and witness materials test contamination; paired altered and unaltered material can test process history. Filling every container with visually distinctive rocks can produce a poor scientific dataset.

Representativeness must be stated rather than assumed. A spectacular clast transported downslope may be scientifically valuable but cannot automatically represent the bedrock beneath the rover. The provenance statement becomes part of the measurement.

Traverse map with contacts and protected return

Mapped contact
confidence + alternatives



Mapped contacts, science stops and a protected return route are combined on one field traverse diagram. Pedagogical synthesis by Delta-Sierra from the primary sources cited in this dossier; not a mission-certified drawing.

Chain of custody includes configuration and environment

Traceability extends beyond a sample identifier. Tools, gloves, container lot, cleaning status, airlock transfer, storage temperature and every subdivision can matter. If organics or potential biosignatures are involved, the contamination-control history may be as important as the sample mass.

The field and laboratory teams should share one lineage. If a container is split into several subsamples, each child sample inherits the parent context plus its own handling record. A later analyst should be able to reconstruct the chain without asking the original collector what happened.

Geology is also a siting and construction discipline

Settlement geology must identify competent ground, slope stability, loose material, dust mobility, excavation behaviour and the spatial variability of resources. The ‘best science site’ and ‘best habitat site’ can therefore be different locations.

A site board should separate scientific interest from engineering suitability and then look for conflicts. A volatile-rich deposit can be industrially attractive while creating difficult trafficability or contamination control. A lava plain can be operationally convenient while offering weaker access to diverse science targets.

Uncertainty belongs on the map

Primary-source bridge: [NASA — Artemis geology field training](#).

Field maps often imply crisp boundaries that the terrain does not actually reveal. Use confidence, inferred contacts and alternative interpretations explicitly. When a contact is buried, draw what is observed and mark the extrapolation as inferred rather than pretending the boundary was measured.

The same practice applies to hypotheses. A team that records only its preferred interpretation will later struggle to understand why a surprising laboratory result matters. Competing hypotheses make disconfirming evidence useful rather than embarrassing.

The debrief converts field experience into institutional knowledge

The traverse is not finished at airlock closure. The crew should reconcile voice notes, imagery, sample identifiers, route changes, instrument files and safety deviations while memory is fresh. Missing metadata should be flagged rather than silently invented.

The debrief also updates the next traverse. A slope that looked benign from orbit, an unexpectedly slow sampling method or a recurring navigation ambiguity becomes a planning input. The scientific campaign improves when each sortie teaches the next one how to ask better questions.

Qualification casebook — six board decisions

1. **A bright vein lies 300 m beyond the planned turnaround.** The feature could test the leading aqueous hypothesis.

▼ Reasoned disposition — open after making your own decision

Protect return and contingency first. If the target cannot fit without consuming the reserve, defer it and capture the observations needed to plan a dedicated later traverse.

2. **2. A loose cobble contains an unusual mineral.** Its source outcrop is unknown.

▼ Reasoned disposition — open after making your own decision

Collect it only with an explicit transported-clast provenance. Do not use it as evidence for the local bedrock without an independent source relationship.

3. **3. Two samples from the same layer disagree strongly.** Both analytical runs pass instrument checks.

▼ Reasoned disposition — open after making your own decision

Revisit spatial context, texture and sample heterogeneity before treating one result as an error. The disagreement may reveal real local variability.

4. **4. A sample container label is readable but one transfer was not logged.** The chain has a gap.

▼ Reasoned disposition — open after making your own decision

Quarantine the evidentiary status of the affected sample until the transfer can be reconstructed from independent records; never fill the gap from memory as if it were observed fact.

5. **5. A proposed habitat site lies on scientifically rich layered terrain.** The ground is irregular and excavation uncertain.

▼ Reasoned disposition — open after making your own decision

Separate science value from engineering suitability. Preserve access to the terrain while evaluating a more stable nearby construction zone.

6. **6. An orbital contact disappears under dust at EVA scale.** The map had shown it as certain.

▼ Reasoned disposition — open after making your own decision

Downgrade the local boundary to inferred, document the observation limit and seek a second line of evidence rather than forcing the field data to match the pre-mission map.

Mastery studio — four extended review problems

Use these field problems to protect the chain from observation to interpretation: decide what evidence is missing before opening the reasoned disposition.

1. **Competing depositional histories.** A layered outcrop could represent repeated water-laid sediment or reworked impact material. Design a field plan that discriminates between the hypotheses without assuming either one is true.

▼ Extended reasoned answer — open after attempting the problem

Begin by listing observations that should differ between the hypotheses: lateral continuity, sorting, grain rounding, bedding geometry, clast types, cross-cutting relations, mineral distribution and association with nearby landforms. Map the contact before sampling, then choose stations that maximise contrast rather than simply collecting the most accessible material. Include at least one sample from a transition or boundary. The field notebook should record which observation supports or weakens each hypothesis. The final conclusion can remain uncertain; the objective is to make the uncertainty traceable and testable.

2. **Representativeness under severe sample limits.** Only four sealed containers remain, but the traverse crosses three geologic units and one alteration vein. Explain how you would allocate them.

▼ Extended reasoned answer — open after attempting the problem

Do not allocate one container per visually striking target by default. Define the science questions first. One unit may require a replicate to distinguish internal variability, while another may already be well characterised by prior samples. The vein may deserve a paired vein-plus-host comparison rather than a stand-alone fragment. Preserve

contamination controls when organics or volatiles matter. Record the samples you deliberately did not take and why. A small but hypothesis-driven set can carry more information than four unrelated specimens.

3. **3. Map revision after field contradiction.** Orbital mapping predicts a continuous contact, but the crew finds the expected boundary absent across two consecutive stations.

▼ Extended reasoned answer — open after attempting the problem

Treat the field observation as a reason to update the map, not as a failure to follow it. Check whether dust, slope deposits or limited exposure could hide the contact. Record the boundary as inferred or uncertain over the affected interval and seek an independent observation at another scale. If the contact truly disappears, revise the geological model and identify which previous conclusions depended on continuity. The map is a living evidence model; its value comes from being corrected when the terrain disagrees.

4. **4. Contamination discovered after sampling.** A tool used for a biosignature-sensitive sample is later found to have bypassed one cleaning step. The sample itself looks normal.

▼ Extended reasoned answer — open after attempting the problem

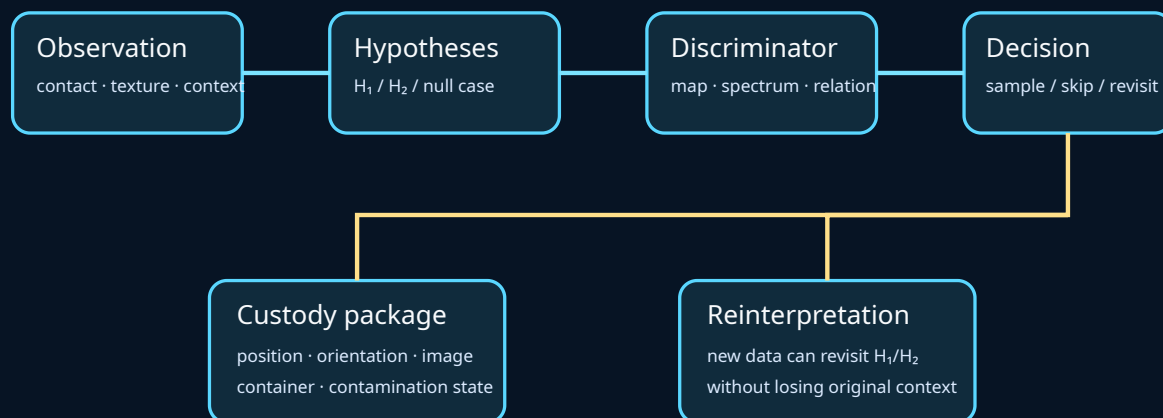
Preserve the sample physically but downgrade or quarantine its evidentiary status. Trace every other sample touched by the same tool, review witness and blank materials, and document the exact cleaning deviation. Do not erase the sample from the campaign: it may remain useful for mineralogy or other analyses that are less sensitive to the contamination pathway. The key is to prevent one compromised chain from contaminating the interpretation of the entire field campaign.

Field evidence under uncertainty — design samples that can still answer a question years later

A good traverse can return many rocks and still fail scientifically if context, custody or hypothesis logic is weak. The operational layer deepens the field-science module around a stricter standard: each sample must preserve the evidence needed for later interpretation, including the

possibility that the original field hypothesis was wrong.

Sample campaign decision tree — collect evidence, not souvenirs



A scientifically valuable sample carries the observation chain that makes later interpretation reproducible.

Decision atlas — Field evidence under uncertainty — design samples that can still answer a question years later. Pedagogical synthesis by Delta-Sierra; use the full-size link for fine labels.

A null result can be scientifically valuable

Field teams naturally prefer spectacular targets, but a campaign designed only to confirm an exciting hypothesis becomes biased. A discriminating traverse should include places where the expected feature is absent, boundaries between units and boring controls. Those observations define the spatial extent of a process and can falsify an interpretation.

The learner should therefore write the expected observation under H₁, under H₂ and under a plausible null case before choosing the sample. If every possible outcome is described as supporting the preferred story, the hypothesis is not actually being tested.

Sampling density should follow spatial variability

One sample cannot represent a heterogeneous outcrop, and twenty samples may be wasteful if the unit is homogeneous. Sampling density should be tied to the question and the observed scale of variation: grain size, alteration, bedding, fractures, contact distance or spectral change.

A field map can mark where uncertainty changes rapidly. That is often where an additional sample has the highest information value. [NASA/NTRS field-geology training material](#) is used here as a primary bridge for contextual observation and field reasoning.

Contamination control begins before the container opens

The sample record should distinguish environmental contamination, tool transfer, suit/rover contact, container background and laboratory handling. Cleanliness is not binary; the question is whether later investigators can identify plausible contamination pathways and interpret measurements accordingly.

That means logging tool history, gloves or interfaces used, container identity, sealing event and any anomaly such as dust intrusion or dropped hardware. A scientifically important sample with weak contamination records may still be useful, but its claims must be narrower.

Chain of custody preserves the original question

Coordinates and a sample number are not enough. The custody package should preserve orientation where relevant, scale images, field sketch, unit/contact relationship, instrument readings, acquisition sequence and the hypothesis being tested. Later investigators may reject the field interpretation but still recover value if the observations are intact.

This is why digital and physical identifiers must stay linked. A mislabeled image can sever the reasoning chain even if the rock itself is pristine.

The debrief should explicitly search for disconfirming evidence

After the traverse, the team compares what was predicted with what was observed. It records failed predictions, changed interpretations and unresolved contradictions. The objective is not to defend the plan but to improve the geological model.

A debrief that only celebrates completed targets cannot distinguish field success from schedule completion. [NASA planetary-analog material](#) provides a primary bridge for using terrestrial field contexts to train planetary observation while preserving the distinction between analog and Mars itself.

Operational review board — five decisions to defend

1. **Spectacular vein, weak context.** A bright vein is easy to sample but its relationship to surrounding units is unclear.

▼ Reasoned disposition — open after making your own decision

Map the contact and obtain contextual observations before consuming scarce sample volume.

2. **Control sample looks boring.** A nearby unaltered unit appears scientifically uninteresting.

▼ Reasoned disposition — open after making your own decision

Keep the control if it discriminates alteration from background composition; boring controls can make the exciting sample interpretable.

3. **Tool touched a previous unknown sample.** The next target is contamination-sensitive.

▼ Reasoned disposition — open after making your own decision

Record the event, clean or replace the interface under protocol, and preserve the contamination history rather than silently treating the tool as clean.

4. **Sample bag label and image timestamp disagree.** The physical sample is sealed.

▼ Reasoned disposition — open after making your own decision

HOLD high-confidence interpretation until the identity conflict is reconciled from redundant records. Do not invent certainty.

5. **Field hypothesis fails.** The predicted mineral signal is absent at multiple discriminating sites.

▼ Reasoned disposition — open after making your own decision

Document the null result and revise the model. A failed hypothesis is a scientific result if the test was valid.

Mission rehearsal notebook — reason through evidence before revealing the disposition

Notebook drill — competing stratigraphic interpretations

Two teams map the same contact differently: one interprets an erosional unconformity, the other a depositional transition. Before sampling, each team lists the observations that would discriminate the interpretations—truncation, clast provenance, bedding continuity, alteration patterns and cross-cutting relationships. The traverse is then designed to visit locations where those observations should differ most strongly. Samples are selected only after the contact geometry is documented. The exercise teaches that a field dispute is productive when it produces a better test. Consensus before evidence is not the goal.

Notebook drill — scarce sample mass

The mission can return only a small mass of carefully sealed samples. The team therefore ranks samples by information value rather than visual novelty. A sample that duplicates an already secure unit may be lower priority than a boundary sample that can distinguish two histories. The ranking records which scientific question each candidate addresses, whether contextual imaging is complete, contamination risk and whether an alternative measurement can answer the same question without consuming sample capacity. This makes sample selection auditable instead of personality-driven.

Notebook drill — later laboratory result contradicts the field model

Months after collection, laboratory mineralogy conflicts with the field interpretation. Because the custody package preserved orientation, images, maps and competing hypotheses, the sample can be reinterpreted without repeating the EVA. The correct institutional response is to update the geologic model and trace which future sampling decisions depended on the old interpretation. The value of field context becomes most visible when the original hypothesis is wrong.

Primary-source bridges used in this operational rehearsal

- [NASA/NTRS — planetary field geology training](#)
- [NASA — Planetary analogs](#)

Closure standard. The learner can explain the evidence chain, identify the limiting uncertainty or dependency, defend a degraded-state decision and state what a real mission would still need to verify.

Closure review — field science must remain reproducible after the crew leaves the outcrop

The final standard for this module is not “the crew collected interesting rocks”. A scientifically defensible campaign preserves the relationship between observation, location, orientation, instrument data, contamination history, competing hypotheses and the physical sample. The sample may be analysed years later by people who never saw the site. Their ability to reconstruct the question depends on the field record.

Observation and inference should never be stored as the same field

“Layer is 12 centimetres thick and truncates the unit below” is an observation. “This is an erosional surface” is an interpretation. Both matter, but they must remain distinguishable so later evidence can change the interpretation without erasing the original field fact. The same discipline applies to colour, texture, vein relationships, clast shape and apparent alteration.

Context is a measurement

A sample identifier without location, orientation, imagery and relation to contacts is scientifically poorer than a smaller sample with complete context. The closure checklist therefore requires before/after imagery, map position, orientation when relevant, nearby unit description, instrument settings and custody history. If the context record is incomplete, that limitation follows the sample into the archive.

Planetary field work needs an explicit contamination story

The team records which tools touched the material, whether containers were opened, what cleaning state existed and which environmental or habitat sources could contaminate the sample. This is not the same thing as declaring a planetary-protection category; it is the local evidence chain required to interpret later laboratory results honestly.

▼ Closure case — a later laboratory result contradicts the field interpretation

Retain the laboratory result and revisit the stored observations. The field interpretation is a hypothesis, not a property of the sample. Because context, custody and competing hypotheses were preserved, the mission can update the geologic model instead of rewriting the original notes.

Closure drill — map uncertainty as part of the product

A geologic map should distinguish where a contact was directly observed, where it is inferred between observations and where the uncertainty is large enough to change a traverse decision. This avoids drawing one confident line through sparse data. The same discipline applies to unit boundaries under dust cover and to extrapolating a layer across terrain that has not been visited.

Closure drill — sample triage under return-mass pressure

Rank samples by the question they can answer, uniqueness of context, ability to discriminate hypotheses, contamination risk and whether a destructive measurement would consume a rare specimen. The “most spectacular” rock can be lower priority than a modest boundary sample that separates two competing histories.

R74 PEDAGOGICAL AND QUANTITATIVE SUPPLEMENT

Quantitative parity laboratory — ten field-geology calculations

These mini-lessons close the FR/EN calculation gap with ten reproducible tools for chronology, samples, mapping, metadata, resources and uncertainty. Every equation is taught as a decision tool rather than decorative notation.

Crater density — compare surfaces of different size

$$D_{\text{crater}} = N_{\text{crater}} / A$$

1 — Concrete question

For **Crater density — compare surfaces of different size**, how does $D_{\text{crater}} = N_{\text{crater}} / A$ inform field chronology and map-unit comparison and the operational choice “Use crater density as one line of relative-age evidence, never as a stand-alone absolute clock.”?

2 — Intuition without symbols

Intuition. Two surfaces cannot be compared fairly by crater count alone if their mapped areas differ. What matters is how concentrated the counted craters are over the same type of terrain and the same counting threshold.

3 — Quantities first

N_{crater} is the number of counted craters; A is the mapped area; D_{crater} is crater density.

4 — Formula

$$D_{\text{crater}} = N_{\text{crater}} / A$$

5 — Read aloud

“ D_{crater} equals N_{crater} divided by A .”

6 — Symbols

Symbol map for Crater density — compare surfaces of different size. N_{crater} is the number of counted craters; A is the mapped area; D_{crater} is crater density.

7 — Pronunciation

Pronunciation. Say $D_{\text{crater}} = N_{\text{crater}} / A$. For *Crater density — compare surfaces of different size*, use the step-three names tied to field chronology and map-unit comparison. Speak each *Crater density — compare surfaces of different size* unit with the quantity it measures.

8 — Units

count / km² = craters per km²

9 — Convention

Convention. For *Crater density — compare surfaces of different size*, keep field chronology and map-unit comparison on one declared boundary. Apply $D_{\text{crater}} = N_{\text{crater}} / A$ under that convention. Counts are meaningful only for the same crater-diameter threshold, mapping unit and preservation state.

10 — Why this operation

Why this operation. $D_{\text{crater}} = N_{\text{crater}} / A$ answers the *Crater density — compare surfaces of different size* question because it represents field chronology and map-unit comparison. In this case it yields: A density of 0.20 craters/km² in this defined diameter range and mapped unit.

11 — Assumptions

Assumptions. Treat the *Crater density — compare surfaces of different size* values as one teaching case. For field chronology and map-unit comparison, keep a single physical or operational boundary. Counts are meaningful only for the same crater-diameter threshold, mapping unit and preservation state.

12 — Unit check

Unit check. Reduce $D_{\text{crater}} = N_{\text{crater}} / A$ for *Crater density — compare surfaces of different size*. The required dimension is $\text{count} / \text{km}^2 = \text{craters per km}^2$. A different dimension invalidates “A density of 0.20 craters/km² in this defined diameter range and mapped unit.”.

13 — Numerical case

$$N_{\text{crater}} = 42$$

$$A = 210 \text{ km}^2$$

$$D_{\text{crater}} = 42 / 210 = 0.20 \text{ craters/km}^2$$

14 — Why each operation

Why each operation. For *Crater density — compare surfaces of different size*, substitute $N_{\text{crater}} = 42$; $A = 210 \text{ km}^2$; $D_{\text{crater}} = 42 / 210 = 0.20 \text{ craters/km}^2$ into $D_{\text{crater}} = N_{\text{crater}} / A$. Then verify the independent statement “ $0.20 \times 210 = 42 \text{ craters}$ ”.

15 — Algebra check

Algebra check. Reverse $D_{\text{crater}} = N_{\text{crater}} / A$ for *Crater density — compare surfaces of different size* using “ $0.20 \times 210 = 42 \text{ craters}$ ”. The recovered input should follow “If the same 42 craters are spread over twice the area, density halves.”. If not, recheck units and boundaries.

16 — Mental estimate

Mental estimate. Round the dominant inputs for *Crater density — compare surfaces of different size*. Compare that rough scale with “A density of 0.20 craters/km² in this defined diameter range and mapped unit.”. If they diverge sharply, inspect $D_{\text{crater}} = N_{\text{crater}} / A$ for units, signs or boundaries.

17 — Interpretation

Interpretation. For *Crater density — compare surfaces of different size*, A density of 0.20 craters/km² in this defined diameter range and mapped unit. Operationally: Use crater density as one line of relative-age evidence, never as a stand-alone absolute clock. The interpretation remains limited by “Counts are meaningful only for the same crater-diameter threshold, mapping unit and preservation state.”.

18 — What it does not prove

What it does not prove. *Crater density — compare surfaces of different size* cannot support claims outside field chronology and map-unit comparison. Counts are meaningful only for the same crater-diameter threshold, mapping unit and preservation state. Use the result only to justify: Use crater density as one line of relative-age evidence, never as a stand-alone absolute clock.

19 — Sensitivity or limit case

If the same 42 craters are spread over twice the area, density halves.

20 — Practice

Guided exercise — Crater density — compare surfaces of different size. A second unit contains 30 counted craters over 120 km². Calculate its density.

Guided correction — Crater density — compare surfaces of different size

1. $D = 30 / 120 = 0.25 \text{ craters/km}^2$.
2. The numerical comparison is valid only if the counting rules and diameter threshold are the same.

Autonomous exercise — Crater density — compare surfaces of different size. Build a second case from “If the same 42 craters are spread over twice the area, density halves.”. Re-evaluate $D_{\text{crater}} = N_{\text{crater}} / A$. Name the changed input. Decide whether “Use crater density as one line of relative-age evidence, never as a stand-alone absolute clock.” still follows.

Autonomous correction — Crater density — compare surfaces of different size

For *Crater density — compare surfaces of different size*, state the altered case. Preserve $\text{count} / \text{km}^2 = \text{craters per km}^2$. Match the direction in “If the same 42 craters are spread over twice the area, density halves.”. Respect “Counts are meaningful only for the same crater-diameter threshold, mapping unit and preservation state.”. Finish by retaining or revising: Use crater density as one line of relative-age evidence, never as a stand-alone absolute clock.

21 — Mission decision

Use crater density as one line of relative-age evidence, never as a stand-alone absolute clock.

Rock bulk density — connect sample mass to volume

$$\rho = m / V$$

1 — Concrete question

For **Rock bulk density — connect sample mass to volume**, how does $\rho = m / V$ inform rock identification, porosity screening and engineering context and the operational choice “Use density to support, not replace, petrographic and mineralogical interpretation.”?

2 — Intuition without symbols

Intuition. A rock that packs a lot of mass into a small bulk volume is denser than one with the same mass spread through a larger volume. Pores, fractures and ice can therefore change the measured bulk value even when the mineral grains are similar.

3 — Quantities first

m is sample mass; V is bulk sample volume; rho is bulk density.

4 — Formula

$$\rho = m / V$$

5 — Read aloud

“rho equals m divided by V.”

6 — Symbols

Symbol map for Rock bulk density — connect sample mass to volume. m is sample mass; V is bulk sample volume; rho is bulk density.

7 — Pronunciation

Pronunciation. Say $\rho = m / V$. For *Rock bulk density — connect sample mass to volume*, use the step-three names tied to rock identification, porosity screening and engineering context. Speak each *Rock bulk density — connect sample mass to volume* unit with the quantity it measures.

8 — Units

$$\text{kg} / \text{m}^3 = \text{kg/m}^3$$

9 — Convention

Convention. For *Rock bulk density — connect sample mass to volume*, keep rock identification, porosity screening and engineering context on one declared boundary. Apply $\rho = m / V$ under that convention. Bulk density depends on pores, fractures, moisture/ice and the volume method; it is not automatically mineral density.

10 — Why this operation

Why this operation. $\rho = m / V$ answers the *Rock bulk density — connect sample mass to volume* question because it represents rock identification, porosity screening and engineering context. In this case it yields: The sample bulk density is 3,120 kg/m³.

11 — Assumptions

Assumptions. Treat the *Rock bulk density — connect sample mass to volume* values as one teaching case. For rock identification, porosity screening and engineering context, keep a single physical or operational boundary. Bulk density depends on pores, fractures, moisture/ice and the volume method; it is not automatically mineral density.

12 — Unit check

Unit check. Reduce $\rho = m / V$ for *Rock bulk density — connect sample mass to volume*. The required dimension is $\text{kg} / \text{m}^3 = \text{kg/m}^3$. A different dimension invalidates “The sample bulk density is 3,120 kg/m³.”.

13 — Numerical case

$$m = 7.80 \text{ kg}$$

$$V = 0.00250 \text{ m}^3$$

$$\rho = 7.80 / 0.00250 = 3,120 \text{ kg/m}^3$$

14 — Why each operation

Why each operation. For *Rock bulk density — connect sample mass to volume*, substitute $m = 7.80 \text{ kg}$; $V = 0.00250 \text{ m}^3$; $\rho = 7.80 / 0.00250 = 3,120 \text{ kg/m}^3$ into $\rho = m / V$. Then verify the independent statement “ $3,120 \times 0.00250 = 7.80 \text{ kg}$ ”.

15 — Algebra check

Algebra check. Reverse $\rho = m / V$ for *Rock bulk density — connect sample mass to volume* using “ $3,120 \times 0.00250 = 7.80 \text{ kg}$ ”. The recovered input should follow “At fixed mass, a 10% larger measured volume lowers computed density by about 9.1%.”. If not, recheck units and boundaries.

16 — Mental estimate

Mental estimate. Round the dominant inputs for *Rock bulk density — connect sample mass to volume*. Compare that rough scale with “The sample bulk density is 3,120 kg/m³.”. If they diverge sharply, inspect $\rho = m / V$ for units, signs or boundaries.

17 — Interpretation

Interpretation. For *Rock bulk density — connect sample mass to volume*, The sample bulk density is 3,120 kg/m³. Operationally: Use density to support, not replace, petrographic and mineralogical interpretation. The interpretation remains limited by “Bulk density depends on pores, fractures, moisture/ice and the volume method; it is not automatically mineral density.”.

18 — What it does not prove

What it does not prove. *Rock bulk density — connect sample mass to volume* cannot support claims outside rock identification, porosity screening and engineering context. Bulk density depends on pores, fractures, moisture/ice and the volume method; it is not automatically mineral density. Use the result only to justify: Use density to support, not replace, petrographic and mineralogical interpretation.

19 — Sensitivity or limit case

At fixed mass, a 10% larger measured volume lowers computed density by about 9.1%.

20 — Practice

Guided exercise — Rock bulk density — connect sample mass to volume. A 5.40 kg sample occupies 0.00200 m³. Calculate bulk density.

Guided correction — Rock bulk density — connect sample mass to volume

1. $\rho = 5.40 / 0.00200 = 2,700 \text{ kg/m}^3$.
2. Report the volume method because irregular rocks can make volume the dominant uncertainty.

Autonomous exercise — Rock bulk density — connect sample mass to volume. Build a second case from “At fixed mass, a 10% larger measured volume lowers computed density by about 9.1%.”. Re-evaluate $\rho = m / V$. Name the changed input. Decide whether “Use density to support, not replace, petrographic and mineralogical interpretation.” still follows.

Autonomous correction — Rock bulk density — connect sample mass to volume

For *Rock bulk density — connect sample mass to volume*, state the altered case. Preserve $\text{kg} / \text{m}^3 = \text{kg/m}^3$. Match the direction in “At fixed mass, a 10% larger measured volume lowers computed density by about 9.1%.”. Respect “Bulk density depends on pores, fractures, moisture/ice and the volume method; it is not automatically mineral density.”. Finish by retaining or revising: Use density to support, not replace, petrographic and mineralogical interpretation.

21 — Mission decision

Use density to support, not replace, petrographic and mineralogical interpretation.

Stratigraphic thickness from two elevations

$$H = z_{\text{top}} - z_{\text{base}}$$

1 — Concrete question

For **Stratigraphic thickness from two elevations**, how does $H = z_{\text{top}} - z_{\text{base}}$ inform measuring a bed or unit thickness in a common vertical reference and the operational choice “Keep the geometric definition explicit so later teams can reproduce the section.”?

2 — Intuition without symbols

Intuition. The vertical separation between the bottom and top of a layer gives a first measure of thickness. That simple height difference is useful only while remembering that a tilted layer can be longer along its true normal direction.

3 — Quantities first

z_{top} is top elevation; z_{base} is base elevation; H is vertical thickness.

4 — Formula

$$H = z_{\text{top}} - z_{\text{base}}$$

5 — Read aloud

“ H equals z top minus z base.”

6 — Symbols

Symbol map for Stratigraphic thickness from two elevations. z_{top} is top elevation; z_{base} is base elevation; H is vertical thickness.

7 — Pronunciation

Pronunciation. Say $H = z_{\text{top}} - z_{\text{base}}$. For *Stratigraphic thickness from two elevations*, use the step-three names tied to measuring a bed or unit thickness in a common vertical reference. Speak each *Stratigraphic thickness from two elevations* unit with the quantity it measures.

8 — Units

$$\text{m} - \text{m} = \text{m}$$

9 — Convention

Convention. For *Stratigraphic thickness from two elevations*, keep measuring a bed or unit thickness in a common vertical reference on one declared boundary. Apply $H = z_{\text{top}} - z_{\text{base}}$ under that convention. This is vertical separation, not true bed thickness if the layer is inclined or the reference surfaces are not parallel.

10 — Why this operation

Why this operation. $H = z_{\text{top}} - z_{\text{base}}$ answers the *Stratigraphic thickness from two elevations* question because it represents measuring a bed or unit thickness in a common vertical reference. In this case it yields: The vertical separation is 5.5 m.

11 — Assumptions

Assumptions. Treat the *Stratigraphic thickness from two elevations* values as one teaching case. For measuring a bed or unit thickness in a common vertical reference, keep a single physical or operational boundary. This is vertical separation, not true bed thickness if the layer is inclined or the reference surfaces are not parallel.

12 — Unit check

Unit check. Reduce $H = z_{\text{top}} - z_{\text{base}}$ for *Stratigraphic thickness from two elevations*. The required dimension is $\text{m} - \text{m} = \text{m}$. A different dimension invalidates “The vertical separation is 5.5 m.”.

13 — Numerical case

$$z_{\text{top}} = 14.2 \text{ m}$$

$$z_{\text{base}} = 8.7 \text{ m}$$

$$H = 14.2 - 8.7 = 5.5 \text{ m}$$

14 — Why each operation

Why each operation. For *Stratigraphic thickness from two elevations*, substitute $z_{\text{top}} = 14.2 \text{ m}$; $z_{\text{base}} = 8.7 \text{ m}$; $H = 14.2 - 8.7 = 5.5 \text{ m}$ into $H = z_{\text{top}} - z_{\text{base}}$. Then verify the independent statement “ $8.7 + 5.5 = 14.2 \text{ m}$ ”.

15 — Algebra check

Algebra check. Reverse $H = z_{\text{top}} - z_{\text{base}}$ for *Stratigraphic thickness from two elevations* using “ $8.7 + 5.5 = 14.2 \text{ m}$ ”. The recovered input should follow “A +0.2 m shift in only z_{top} increases H by 0.2 m.”. If not, recheck units and boundaries.

16 — Mental estimate

Mental estimate. Round the dominant inputs for *Stratigraphic thickness from two elevations*. Compare that rough scale with “The vertical separation is 5.5 m.”. If they diverge sharply, inspect $H = z_{\text{top}} - z_{\text{base}}$ for units, signs or boundaries.

17 — Interpretation

Interpretation. For *Stratigraphic thickness from two elevations*, The vertical separation is 5.5 m. Operationally: Keep the geometric definition explicit so later teams can reproduce the section. The interpretation remains limited by “This is vertical separation, not true bed thickness if the layer is inclined or the reference surfaces are not parallel.”.

18 — What it does not prove

What it does not prove. *Stratigraphic thickness from two elevations* cannot support claims outside measuring a bed or unit thickness in a common vertical reference. This is vertical separation, not true bed thickness if the layer is inclined or the reference surfaces are not parallel. Use the result only to justify: Keep the geometric definition explicit so later teams can reproduce the section.

19 — Sensitivity or limit case

A +0.2 m shift in only z_{top} increases H by 0.2 m.

20 — Practice

Guided exercise — Stratigraphic thickness from two elevations. A unit base is at 31.4 m and its top at 38.1 m. Find vertical thickness.

Guided correction — Stratigraphic thickness from two elevations

1. $H = 38.1 - 31.4 = 6.7$ m.
2. If the bed dips, document orientation before calling 6.7 m the true stratigraphic thickness.

Autonomous exercise — Stratigraphic thickness from two elevations. Build a second case from “A +0.2 m shift in only z_{top} increases H by 0.2 m.”. Re-evaluate $H = z_{\text{top}} - z_{\text{base}}$. Name the changed input. Decide whether “Keep the geometric definition explicit so later teams can reproduce the section.” still follows.

Autonomous correction — Stratigraphic thickness from two elevations

For *Stratigraphic thickness from two elevations*, state the altered case. Preserve $m - m = m$. Match the direction in “A +0.2 m shift in only z_{top} increases H by 0.2 m.”. Respect “This is vertical separation, not true bed thickness if the layer is inclined or the reference surfaces are not parallel.”. Finish by retaining or revising: Keep the geometric definition explicit so later teams can reproduce the section.

21 — Mission decision

Keep the geometric definition explicit so later teams can reproduce the section.

Altered-mass fraction — quantify how much of a sample changed

$$f_{alt} = m_{alt} / m_{total}$$

1 — Concrete question

For **Altered-mass fraction — quantify how much of a sample changed**, how does $f_{alt} = m_{alt} / m_{total}$ inform screening the proportion of altered material in a collected sample and the operational choice “Use the fraction to prioritize follow-up analyses, while preserving unaltered controls.”?

2 — Intuition without symbols

Intuition. A sample can contain both relatively fresh and visibly or chemically altered material. Comparing the altered portion with the whole sample turns that observation into a reproducible fraction for follow-up work.

3 — Quantities first

m_{alt} is mass classified as altered; m_{total} is total sample mass; f_{alt} is the altered fraction.

4 — Formula

$$f_{alt} = m_{alt} / m_{total}$$

5 — Read aloud

“ f_{alt} equals m_{alt} divided by m_{total} .”

6 — Symbols

Symbol map for Altered-mass fraction — quantify how much of a sample changed. m_{alt} is mass classified as altered; m_{total} is total sample mass; f_{alt} is the altered fraction.

7 — Pronunciation

Pronunciation. Say $f_{alt} = m_{alt} / m_{total}$. For *Altered-mass fraction — quantify how much of a sample changed*, use the step-three names tied to screening the proportion of altered material in a collected sample. Speak each *Altered-mass fraction — quantify how much of a sample changed* unit with the quantity it measures.

8 — Units

kg / kg = dimensionless fraction

9 — Convention

Convention. For *Altered-mass fraction — quantify how much of a sample changed*, keep screening the proportion of altered material in a collected sample on one declared boundary. Apply $f_{alt} = m_{alt} / m_{total}$ under that convention. The result inherits the classification rule: visually altered, spectrally altered and chemically altered are not interchangeable labels.

10 — Why this operation

Why this operation. $f_{alt} = m_{alt} / m_{total}$ answers the *Altered-mass fraction — quantify how much of a sample changed* question because it represents screening the proportion of altered material in a collected sample. In this case it yields: Fifteen percent of the classified sample mass is in the altered category.

11 — Assumptions

Assumptions. Treat the *Altered-mass fraction — quantify how much of a sample changed* values as one teaching case. For screening the proportion of altered material in a collected sample, keep a single physical or operational boundary. The result inherits the classification rule: visually altered, spectrally altered and chemically altered are not interchangeable labels.

12 — Unit check

Unit check. Reduce $f_{alt} = m_{alt} / m_{total}$ for *Altered-mass fraction — quantify how much of a sample changed*. The required dimension is $kg / kg = \text{dimensionless fraction}$. A different dimension invalidates “Fifteen percent of the classified sample mass is in the altered category.”.

13 — Numerical case

$$m_{alt} = 1.80 \text{ kg}$$

$$m_{total} = 12.0 \text{ kg}$$

$$f_{alt} = 1.80 / 12.0 = 0.150 = 15.0\%$$

14 — Why each operation

Why each operation. For *Altered-mass fraction — quantify how much of a sample changed*, substitute $m_{alt} = 1.80 \text{ kg}$; $m_{total} = 12.0 \text{ kg}$; $f_{alt} = 1.80 / 12.0 = 0.150 = 15.0\%$ into $f_{alt} = m_{alt} / m_{total}$. Then verify the independent statement “ $0.150 \times 12.0 = 1.80 \text{ kg}$ ”.

15 — Algebra check

Algebra check. Reverse $f_{alt} = m_{alt} / m_{total}$ for *Altered-mass fraction — quantify how much of a sample changed* using “ $0.150 \times 12.0 = 1.80 \text{ kg}$ ”. The recovered input should follow “If altered mass rises to 2.4 kg with total mass unchanged, the fraction becomes 20%.”. If not, recheck units and boundaries.

16 — Mental estimate

Mental estimate. Round the dominant inputs for *Altered-mass fraction — quantify how much of a sample changed*. Compare that rough scale with “Fifteen percent of the classified sample mass is in the altered category.”. If they diverge sharply, inspect $f_{alt} = m_{alt} / m_{total}$ for units, signs or boundaries.

17 — Interpretation

Interpretation. For *Altered-mass fraction — quantify how much of a sample changed*, Fifteen percent of the classified sample mass is in the altered category. Operationally: Use the fraction to prioritize follow-up analyses, while preserving unaltered controls. The interpretation remains limited by “The result inherits the classification rule: visually altered, spectrally altered and chemically altered are not interchangeable labels.”.

18 — What it does not prove

What it does not prove. *Altered-mass fraction — quantify how much of a sample changed* cannot support claims outside screening the proportion of altered material in a collected sample. The result inherits the classification rule: visually altered, spectrally altered and chemically altered are not interchangeable labels. Use the result only to justify: Use the fraction to prioritize follow-up analyses, while preserving unaltered controls.

19 — Sensitivity or limit case

If altered mass rises to 2.4 kg with total mass unchanged, the fraction becomes 20%.

20 — Practice

Guided exercise — Altered-mass fraction — quantify how much of a sample changed. A 9.0 kg sample contains 0.90 kg classified as altered. Find the fraction.

Guided correction — Altered-mass fraction — quantify how much of a sample changed

1. $f_{alt} = 0.90 / 9.0 = 0.10 = 10\%$.
2. State the classification criterion with the percentage.

Autonomous exercise — Altered-mass fraction — quantify how much of a sample changed. Build a second case from “If altered mass rises to 2.4 kg with total mass unchanged, the fraction becomes 20%.”. Re-evaluate $f_{alt} = m_{alt} / m_{total}$. Name the changed input. Decide whether “Use the fraction to prioritize follow-up analyses, while preserving unaltered controls.” still follows.

Autonomous correction — Altered-mass fraction — quantify how much of a sample changed

For *Altered-mass fraction — quantify how much of a sample changed*, state the altered case. Preserve $kg / kg = \text{dimensionless fraction}$. Match the direction in “If altered mass rises to 2.4 kg with total mass unchanged, the fraction becomes 20%.”. Respect “The result inherits the classification rule: visually altered, spectrally altered and chemically altered are not interchangeable labels.”. Finish by retaining or revising: Use the fraction to prioritize follow-up analyses, while preserving unaltered controls.

21 — Mission decision

Use the fraction to prioritize follow-up analyses, while preserving unaltered controls.

Map scale as a dimensionless ratio

$$S = d_{\text{map}} / d_{\text{ground}}$$

1 — Concrete question

For **Map scale as a dimensionless ratio**, how does $S = d_{\text{map}} / d_{\text{ground}}$ inform converting a measured map distance into ground distance and the operational choice “Choose scale fine enough to preserve contacts and hazards relevant to the traverse decision.”?

2 — Intuition without symbols

Intuition. A map compresses a large landscape into a small drawing. Scale tells the field team how a distance measured on the map corresponds to the real distance on the ground, provided both are expressed consistently.

3 — Quantities first

d_{map} is distance measured on the map; d_{ground} is the corresponding real distance; S is scale ratio.

4 — Formula

$$S = d_{\text{map}} / d_{\text{ground}}$$

5 — Read aloud

“ S equals d_{map} divided by d_{ground} .”

6 — Symbols

Symbol map for Map scale as a dimensionless ratio. d_{map} is distance measured on the map; d_{ground} is the corresponding real distance; S is scale ratio.

7 — Pronunciation

Pronunciation. Say $S = d_{\text{map}} / d_{\text{ground}}$. For *Map scale as a dimensionless ratio*, use the step-three names tied to converting a measured map distance into ground distance. Speak each *Map scale as a dimensionless ratio* unit with the quantity it measures.

8 — Units

same length unit / same length unit = dimensionless

9 — Convention

Convention. For *Map scale as a dimensionless ratio*, keep converting a measured map distance into ground distance on one declared boundary. Apply $S = d_{\text{map}} / d_{\text{ground}}$ under that convention. The ratio is valid only after converting both distances to the same unit; screen zoom does not change the encoded map scale.

10 — Why this operation

Why this operation. $S = d_{\text{map}} / d_{\text{ground}}$ answers the *Map scale as a dimensionless ratio* question because it represents converting a measured map distance into ground distance. In this case it yields: The example is a 1:40,000 scale map.

11 — Assumptions

Assumptions. Treat the *Map scale as a dimensionless ratio* values as one teaching case. For converting a measured map distance into ground distance, keep a single physical or operational boundary. The ratio is valid only after converting both distances to the same unit; screen zoom does not change the encoded map scale.

12 — Unit check

Unit check. Reduce $S = d_{\text{map}} / d_{\text{ground}}$ for *Map scale as a dimensionless ratio*. The required dimension is $\text{same length unit} / \text{same length unit} = \text{dimensionless}$. A different dimension invalidates “The example is a 1:40,000 scale map.”.

13 — Numerical case

$$d_{\text{map}} = 2.5 \text{ cm} = 0.025 \text{ m}$$

$$d_{\text{ground}} = 1.0 \text{ km} = 1,000 \text{ m}$$

$$S = 0.025 / 1,000 = 0.000025 = 1 / 40,000$$

14 — Why each operation

Why each operation. For *Map scale as a dimensionless ratio*, substitute $d_{\text{map}} = 2.5 \text{ cm} = 0.025 \text{ m}$; $d_{\text{ground}} = 1.0 \text{ km} = 1,000 \text{ m}$; $S = 0.025 / 1,000 = 0.000025 = 1 / 40,000$ into $S = d_{\text{map}} / d_{\text{ground}}$. Then verify the independent statement “ $1,000 \text{ m} / 40,000 = 0.025 \text{ m} = 2.5 \text{ cm}$ ”.

15 — Algebra check

Algebra check. Reverse $S = d_{\text{map}} / d_{\text{ground}}$ for *Map scale as a dimensionless ratio* using “ $1,000 \text{ m} / 40,000 = 0.025 \text{ m} = 2.5 \text{ cm}$ ”. The recovered input should follow “At 1:40,000, 1 cm on the map corresponds to 400 m on the ground.”. If not, recheck units and boundaries.

16 — Mental estimate

Mental estimate. Round the dominant inputs for *Map scale as a dimensionless ratio*. Compare that rough scale with “The example is a 1:40,000 scale map.”. If they diverge sharply, inspect $S = d_{\text{map}} / d_{\text{ground}}$ for units, signs or boundaries.

17 — Interpretation

Interpretation. For *Map scale as a dimensionless ratio*, The example is a 1:40,000 scale map. Operationally: Choose scale fine enough to preserve contacts and hazards relevant to the traverse decision. The interpretation remains limited by “The ratio is valid only after converting both distances to the same unit; screen zoom does not change the encoded map scale.”.

18 — What it does not prove

What it does not prove. *Map scale as a dimensionless ratio* cannot support claims outside converting a measured map distance into ground distance. The ratio is valid only after converting both distances to the same unit; screen zoom does not change the encoded map scale. Use the result only to justify: Choose scale fine enough to preserve contacts and hazards relevant to the traverse decision.

19 — Sensitivity or limit case

At 1:40,000, 1 cm on the map corresponds to 400 m on the ground.

20 — Practice

Guided exercise — Map scale as a dimensionless ratio. On a 1:25,000 map, what ground distance does 3 cm represent?

Guided correction — Map scale as a dimensionless ratio

1. $3 \text{ cm} \times 25,000 = 75,000 \text{ cm} = 750 \text{ m}$.
2. Keep the scale denominator attached to the measurement in the field notebook.

Autonomous exercise — Map scale as a dimensionless ratio. Build a second case from “At 1:40,000, 1 cm on the map corresponds to 400 m on the ground.”. Re-evaluate $S = d_{\text{map}} / d_{\text{ground}}$. Name the changed input. Decide whether “Choose scale fine enough to preserve contacts and hazards relevant to the traverse decision.” still follows.

Autonomous correction — Map scale as a dimensionless ratio

For *Map scale as a dimensionless ratio*, state the altered case. Preserve $\text{same length unit} / \text{same length unit} = \text{dimensionless}$. Match the direction in “At 1:40,000, 1 cm on the map corresponds to 400 m on the ground.”. Respect “The ratio is valid only after converting both distances to the same unit; screen zoom does not change the encoded map scale.”. Finish by retaining or revising: Choose scale fine enough to preserve contacts and hazards relevant to the traverse decision.

21 — Mission decision

Choose scale fine enough to preserve contacts and hazards relevant to the traverse decision.

Metadata completeness — audit whether a sample record can be reconstructed

$$C_{\text{meta}} = N_{\text{filled}} / N_{\text{required}}$$

1 — Concrete question

For **Metadata completeness — audit whether a sample record can be reconstructed**, how does

$C_{\text{meta}} = N_{\text{filled}} / N_{\text{required}}$ inform quality control of field notebooks and sample-chain records and the operational choice “Reject or quarantine records missing provenance-critical fields even when the aggregate percentage looks high.”?

2 — Intuition without symbols

Intuition. A sample record is only as reconstructable as the information preserved with it. Counting completed mandatory fields reveals how much of the required provenance exists, but a single missing critical field can still invalidate the record.

3 — Quantities first

N_{filled} is the number of required fields completed; N_{required} is the total mandatory fields; C_{meta} is completeness.

4 — Formula

$$C_{\text{meta}} = N_{\text{filled}} / N_{\text{required}}$$

5 — Read aloud

“C meta equals N filled divided by N required.”

6 — Symbols

Symbol map for Metadata completeness — audit whether a sample record can be reconstructed.

N_{filled} is the number of required fields completed; N_{required} is the total mandatory fields; C_{meta} is completeness.

7 — Pronunciation

Pronunciation. Say $C_{\text{meta}} = N_{\text{filled}} / N_{\text{required}}$. For *Metadata completeness — audit whether a sample record can be reconstructed*, use the step-three names tied to quality control of field notebooks and sample-chain records. Speak each *Metadata completeness — audit whether a sample record can be reconstructed* unit with the quantity it measures.

8 — Units

fields / fields = dimensionless fraction

9 — Convention

Convention. For *Metadata completeness — audit whether a sample record can be reconstructed*, keep quality control of field notebooks and sample-chain records on one declared boundary. Apply $C_{\text{meta}} = N_{\text{filled}} / N_{\text{required}}$ under that convention. A high percentage can still hide a critical omission; location, orientation or contamination history may be mission-critical fields.

10 — Why this operation

Why this operation. $C_{\text{meta}} = N_{\text{filled}} / N_{\text{required}}$ answers the *Metadata completeness — audit whether a sample record can be reconstructed* question because it represents quality control of field notebooks and sample-chain records. In this case it yields: Ninety percent of required metadata fields are populated.

11 — Assumptions

Assumptions. Treat the *Metadata completeness — audit whether a sample record can be reconstructed* values as one teaching case. For quality control of field notebooks and sample-chain records, keep a single physical or operational boundary. A high percentage can still hide a critical omission; location, orientation or contamination history may be mission-critical fields.

12 — Unit check

Unit check. Reduce $C_{\text{meta}} = N_{\text{filled}} / N_{\text{required}}$ for *Metadata completeness — audit whether a sample record can be reconstructed*. The required dimension is $\text{fields} / \text{fields} = \text{dimensionless fraction}$. A different dimension invalidates “Ninety percent of required metadata fields are populated.”.

13 — Numerical case

$$N_{\text{filled}} = 18$$

$$N_{\text{required}} = 20$$

$$C_{\text{meta}} = 18 / 20 = 0.90 = 90\%$$

14 — Why each operation

Why each operation. For *Metadata completeness — audit whether a sample record can be reconstructed*, substitute $N_{\text{filled}} = 18$; $N_{\text{required}} = 20$; $C_{\text{meta}} = 18 / 20 = 0.90 = 90\%$ into $C_{\text{meta}} = N_{\text{filled}} / N_{\text{required}}$. Then verify the independent statement “ $0.90 \times 20 = 18$ filled fields”.

15 — Algebra check

Algebra check. Reverse $C_{\text{meta}} = N_{\text{filled}} / N_{\text{required}}$ for *Metadata completeness — audit whether a sample record can be reconstructed* using “ $0.90 \times 20 = 18$ filled fields”. The recovered input should follow “Adding one completed field changes completeness from 90% to 95% in this 20-field form.”. If not, recheck units and boundaries.

16 — Mental estimate

Mental estimate. Round the dominant inputs for *Metadata completeness — audit whether a sample record can be reconstructed*. Compare that rough scale with “Ninety percent of required metadata fields are populated.”. If they diverge sharply, inspect $C_{meta} = N_{filled} / N_{required}$ for units, signs or boundaries.

17 — Interpretation

Interpretation. For *Metadata completeness — audit whether a sample record can be reconstructed*, Ninety percent of required metadata fields are populated. Operationally: Reject or quarantine records missing provenance-critical fields even when the aggregate percentage looks high. The interpretation remains limited by “A high percentage can still hide a critical omission; location, orientation or contamination history may be mission-critical fields.”.

18 — What it does not prove

What it does not prove. *Metadata completeness — audit whether a sample record can be reconstructed* cannot support claims outside quality control of field notebooks and sample-chain records. A high percentage can still hide a critical omission; location, orientation or contamination history may be mission-critical fields. Use the result only to justify: Reject or quarantine records missing provenance-critical fields even when the aggregate percentage looks high.

19 — Sensitivity or limit case

Adding one completed field changes completeness from 90% to 95% in this 20-field form.

20 — Practice

Guided exercise — Metadata completeness — audit whether a sample record can be reconstructed. A record has 23 required fields and 21 are complete. Calculate completeness.

Guided correction — Metadata completeness — audit whether a sample record can be reconstructed

1. $C_{\text{meta}} = 21 / 23 \approx 0.913 = 91.3\%$.
2. Then identify which two fields are missing instead of reporting only the percentage.

Autonomous exercise — Metadata completeness — audit whether a sample record can be reconstructed. Build a second case from “Adding one completed field changes completeness from 90% to 95% in this 20-field form.”. Re-evaluate $C_{\text{meta}} = N_{\text{filled}} / N_{\text{required}}$. Name the changed input. Decide whether “Reject or quarantine records missing provenance-critical fields even when the aggregate percentage looks high.” still follows.

Autonomous correction — Metadata completeness — audit whether a sample record can be reconstructed

For *Metadata completeness — audit whether a sample record can be reconstructed*, state the altered case. Preserve $\text{fields} / \text{fields} = \text{dimensionless fraction}$. Match the direction in “Adding one completed field changes completeness from 90% to 95% in this 20-field form.”. Respect “A high percentage can still hide a critical omission; location, orientation or contamination history may be mission-critical fields.”. Finish by retaining or revising: Reject or quarantine records missing provenance-critical fields even when the aggregate percentage looks high.

21 — Mission decision

Reject or quarantine records missing provenance-critical fields even when the aggregate percentage looks high.

Sampling density — relate sample count to surveyed area

$$D_{\text{sample}} = N_{\text{sample}} / A$$

1 — Concrete question

For **Sampling density — relate sample count to surveyed area**, how does $D_{\text{sample}} = N_{\text{sample}} / A$ inform planning whether spatial coverage matches the question being asked and the operational choice “Set density from expected spatial variability and the hypothesis, not from container availability alone.”?

2 — Intuition without symbols

Intuition. Collecting many samples in a small surveyed area produces denser coverage than collecting the same number across a broad region. That average says nothing by itself about whether the points are well distributed.

3 — Quantities first

N_sample is number of independent samples; A is surveyed area; D_sample is sampling density.

4 — Formula

$$D_{\text{sample}} = N_{\text{sample}} / A$$

5 — Read aloud

"D sample equals N sample divided by A."

6 — Symbols

Symbol map for Sampling density — relate sample count to surveyed area. N_sample is number of independent samples; A is surveyed area; D_sample is sampling density.

7 — Pronunciation

Pronunciation. Say $D_{\text{sample}} = N_{\text{sample}} / A$. For *Sampling density — relate sample count to surveyed area*, use the step-three names tied to planning whether spatial coverage matches the question being asked. Speak each *Sampling density — relate sample count to surveyed area* unit with the quantity it measures.

8 — Units

samples / km²

9 — Convention

Convention. For *Sampling density — relate sample count to surveyed area*, keep planning whether spatial coverage matches the question being asked on one declared boundary. Apply $D_{\text{sample}} = N_{\text{sample}} / A$ under that convention. Average density does not prove representative coverage; clustered samples can leave large unsampled zones.

10 — Why this operation

Why this operation. $D_{\text{sample}} = N_{\text{sample}} / A$ answers the *Sampling density — relate sample count to surveyed area* question because it represents planning whether spatial coverage matches the question being asked. In this case it yields: The campaign averages 2.5 samples per square kilometre.

11 — Assumptions

Assumptions. Treat the *Sampling density — relate sample count to surveyed area* values as one teaching case. For planning whether spatial coverage matches the question being asked, keep a single physical or operational boundary. Average density does not prove representative coverage; clustered samples can leave large unsampled zones.

12 — Unit check

Unit check. Reduce $D_{\text{sample}} = N_{\text{sample}} / A$ for *Sampling density — relate sample count to surveyed area*. The required dimension is $\text{samples} / \text{km}^2$. A different dimension invalidates “The campaign averages 2.5 samples per square kilometre.”.

13 — Numerical case

$$N_{\text{sample}} = 15$$

$$A = 6.0 \text{ km}^2$$

$$D_{\text{sample}} = 15 / 6.0 = 2.5 \text{ samples/km}^2$$

14 — Why each operation

Why each operation. For *Sampling density — relate sample count to surveyed area*, substitute $N_{\text{sample}} = 15$; $A = 6.0 \text{ km}^2$; $D_{\text{sample}} = 15 / 6.0 = 2.5 \text{ samples/km}^2$ into $D_{\text{sample}} = N_{\text{sample}} / A$. Then verify the independent statement “ $2.5 \times 6.0 = 15 \text{ samples}$ ”.

15 — Algebra check

Algebra check. Reverse $D_{\text{sample}} = N_{\text{sample}} / A$ for *Sampling density — relate sample count to surveyed area* using “ $2.5 \times 6.0 = 15 \text{ samples}$ ”. The recovered input should follow “Doubling samples at the same area doubles average sampling density.”. If not, recheck units and boundaries.

16 — Mental estimate

Mental estimate. Round the dominant inputs for *Sampling density — relate sample count to surveyed area*. Compare that rough scale with “The campaign averages 2.5 samples per square kilometre.”. If they diverge sharply, inspect $D_{\text{sample}} = N_{\text{sample}} / A$ for units, signs or boundaries.

17 — Interpretation

Interpretation. For *Sampling density — relate sample count to surveyed area*, The campaign averages 2.5 samples per square kilometre. Operationally: Set density from expected spatial variability and the hypothesis, not from container availability alone. The interpretation remains limited by “Average density does not prove representative coverage; clustered samples can leave large unsampled zones.”.

18 — What it does not prove

What it does not prove. *Sampling density — relate sample count to surveyed area* cannot support claims outside planning whether spatial coverage matches the question being asked. Average density does not prove representative coverage; clustered samples can leave large unsampled zones. Use the result only to justify: Set density from expected spatial variability and the hypothesis, not from container availability alone.

19 — Sensitivity or limit case

Doubling samples at the same area doubles average sampling density.

20 — Practice

Guided exercise — Sampling density — relate sample count to surveyed area. Twelve samples cover 3.0 km². Find average sampling density.

Guided correction — Sampling density — relate sample count to surveyed area

1. $D_{\text{sample}} = 12 / 3.0 = 4.0 \text{ samples/km}^2$.
2. Plot the locations before claiming four samples/km² is spatially representative.

Autonomous exercise — Sampling density — relate sample count to surveyed area. Build a second case from “Doubling samples at the same area doubles average sampling density.”. Re-evaluate

$D_{\text{sample}} = N_{\text{sample}} / A$. Name the changed input. Decide whether “Set density from expected spatial variability and the hypothesis, not from container availability alone.” still follows.

Autonomous correction — Sampling density — relate sample count to surveyed area

For *Sampling density — relate sample count to surveyed area*, state the altered case. Preserve $\text{samples} / \text{km}^2$. Match the direction in “Doubling samples at the same area doubles average sampling density.”. Respect “Average density does not prove representative coverage; clustered samples can leave large unsampled zones.”. Finish by retaining or revising: Set density from expected spatial variability and the hypothesis, not from container availability alone.

21 — Mission decision

Set density from expected spatial variability and the hypothesis, not from container availability alone.

Useful-material mass fraction — turn assay mass into grade

$$G = m_{\text{useful}} / m_{\text{sample}}$$

1 — Concrete question

For **Useful-material mass fraction — turn assay mass into grade**, how does $G = m_{\text{useful}} / m_{\text{sample}}$ inform first-pass resource characterization of a sampled material and the operational choice “Use grade only with uncertainty, sampling geometry and processing recovery when screening an ISRU prospect.”?

2 — Intuition without symbols

Intuition. Resource grade asks what share of an analysed sample is actually the target material. A higher useful share can make processing more attractive, but a single sample never proves the grade of an entire deposit.

3 — Quantities first

m_useful is mass of the target constituent; m_sample is total analyzed sample mass; G is mass fraction or grade.

4 — Formula

$$G = m_{\text{useful}} / m_{\text{sample}}$$

5 — Read aloud

"G equals m useful divided by m sample."

6 — Symbols

Symbol map for Useful-material mass fraction — turn assay mass into grade. m_useful is mass of the target constituent; m_sample is total analyzed sample mass; G is mass fraction or grade.

7 — Pronunciation

Pronunciation. Say $G = m_{\text{useful}} / m_{\text{sample}}$. For *Useful-material mass fraction — turn assay mass into grade*, use the step-three names tied to first-pass resource characterization of a sampled material. Speak each *Useful-material mass fraction — turn assay mass into grade* unit with the quantity it measures.

8 — Units

kg / kg = fraction or %

9 — Convention

Convention. For *Useful-material mass fraction — turn assay mass into grade*, keep first-pass resource characterization of a sampled material on one declared boundary. Apply $G = m_{\text{useful}} / m_{\text{sample}}$ under that convention. A sample grade is not an ore-body grade; spatial representativeness, recovery efficiency and processing losses remain separate questions.

10 — Why this operation

Why this operation. $G = m_{\text{useful}} / m_{\text{sample}}$ answers the *Useful-material mass fraction — turn assay mass into grade* question because it represents first-pass resource characterization of a sampled material. In this case it yields: The analyzed sample contains 6.0% target constituent by mass under the stated assay definition.

11 — Assumptions

Assumptions. Treat the *Useful-material mass fraction — turn assay mass into grade* values as one teaching case. For first-pass resource characterization of a sampled material, keep a single physical or operational boundary. A sample grade is not an ore-body grade; spatial representativeness, recovery efficiency and processing losses remain separate questions.

12 — Unit check

Unit check. Reduce $G = m_{\text{useful}} / m_{\text{sample}}$ for *Useful-material mass fraction — turn assay mass into grade*. The required dimension is $\text{kg} / \text{kg} = \text{fraction or } \%$. A different dimension invalidates “The analyzed sample contains 6.0% target constituent by mass under the stated assay definition.”.

13 — Numerical case

$$m_{\text{useful}} = 0.42 \text{ kg}$$

$$m_{\text{sample}} = 7.00 \text{ kg}$$

$$G = 0.42 / 7.00 = 0.060 = 6.0\%$$

14 — Why each operation

Why each operation. For *Useful-material mass fraction — turn assay mass into grade*, substitute $m_{\text{useful}} = 0.42 \text{ kg}$; $m_{\text{sample}} = 7.00 \text{ kg}$; $G = 0.42 / 7.00 = 0.060 = 6.0\%$ into $G = m_{\text{useful}} / m_{\text{sample}}$. Then verify the independent statement “ $0.060 \times 7.00 = 0.42 \text{ kg}$ ”.

15 — Algebra check

Algebra check. Reverse $G = m_{\text{useful}} / m_{\text{sample}}$ for *Useful-material mass fraction — turn assay mass into grade* using “ $0.060 \times 7.00 = 0.42 \text{ kg}$ ”. The recovered input should follow “If the useful mass stays 0.42 kg but total sample rises to 8.4 kg, grade falls to 5.0%.”. If not, recheck units and boundaries.

16 — Mental estimate

Mental estimate. Round the dominant inputs for *Useful-material mass fraction — turn assay mass into grade*. Compare that rough scale with “The analyzed sample contains 6.0% target constituent by mass under the stated assay definition.”. If they diverge sharply, inspect $G = m_{\text{useful}} / m_{\text{sample}}$ for units, signs or boundaries.

17 — Interpretation

Interpretation. For *Useful-material mass fraction — turn assay mass into grade*, The analyzed sample contains 6.0% target constituent by mass under the stated assay definition. Operationally: Use grade only with uncertainty, sampling geometry and processing recovery when screening an ISRU prospect. The interpretation remains limited by “A sample grade is not an ore-body grade; spatial representativeness, recovery efficiency and processing losses remain separate questions.”.

18 — What it does not prove

What it does not prove. *Useful-material mass fraction — turn assay mass into grade* cannot support claims outside first-pass resource characterization of a sampled material. A sample grade is not an ore-body grade; spatial representativeness, recovery efficiency and processing losses remain separate questions. Use the result only to justify: Use grade only with uncertainty, sampling geometry and processing recovery when screening an ISRU prospect.

19 — Sensitivity or limit case

If the useful mass stays 0.42 kg but total sample rises to 8.4 kg, grade falls to 5.0%.

20 — Practice

Guided exercise — Useful-material mass fraction — turn assay mass into grade. A 5.0 kg sample contains 0.35 kg target material. Find grade.

Guided correction — Useful-material mass fraction — turn assay mass into grade

1. $G = 0.35 / 5.0 = 0.070 = 7.0\%$.
2. Do not extrapolate 7% to the site without a defensible sampling model.

Autonomous exercise — Useful-material mass fraction — turn assay mass into grade. Build a second case from “If the useful mass stays 0.42 kg but total sample rises to 8.4 kg, grade falls to 5.0%.”. Re-evaluate $G = m_{\text{useful}} / m_{\text{sample}}$. Name the changed input. Decide whether “Use grade only with uncertainty, sampling geometry and processing recovery when screening an ISRU prospect.” still follows.

Autonomous correction — Useful-material mass fraction — turn assay mass into grade

For *Useful-material mass fraction — turn assay mass into grade*, state the altered case. Preserve $\text{kg} / \text{kg} = \text{fraction or \%}$. Match the direction in “If the useful mass stays 0.42 kg but total sample rises to 8.4 kg, grade falls to 5.0%.”. Respect “A sample grade is not an ore-body grade; spatial representativeness, recovery efficiency and processing losses remain separate questions.”. Finish by retaining or revising: Use grade only with uncertainty, sampling geometry and processing recovery when screening an ISRU prospect.

21 — Mission decision

Use grade only with uncertainty, sampling geometry and processing recovery when screening an ISRU prospect.

Weighted site score — combine criteria without hiding the weights

$$S_{\text{site}} = \text{sum}(w_i \times s_i)$$

1 — Concrete question

For **Weighted site score — combine criteria without hiding the weights**, how does

$S_{\text{site}} = \text{sum}(w_i \times s_i)$ inform transparent multi-criteria comparison of candidate field or settlement sites and the operational choice “Publish weights and sensitivity tests so a review board can see why a site wins.”?

2 — Intuition without symbols

Intuition. A weighted site score makes preferences explicit by giving each criterion an importance and combining the resulting contributions. The method helps compare candidates only when the weights remain visible and are tested for sensitivity.

3 — Quantities first

w_i is criterion weight; s_i is normalized criterion score; the sum combines weighted contributions.

4 — Formula

$$S_{\text{site}} = \text{sum}(w_i \times s_i)$$

5 — Read aloud

"S site equals the sum of w_i times s_i ."

6 — Symbols

Symbol map for Weighted site score — combine criteria without hiding the weights. w_i is criterion weight; s_i is normalized criterion score; the sum combines weighted contributions.

7 — Pronunciation

Pronunciation. Say $S_{\text{site}} = \text{sum}(w_i \times s_i)$. For *Weighted site score — combine criteria without hiding the weights*, use the step-three names tied to transparent multi-criteria comparison of candidate field or settlement sites. Speak each *Weighted site score — combine criteria without hiding the weights* unit with the quantity it measures.

8 — Units

dimensionless when weights and scores are dimensionless

9 — Convention

Convention. For *Weighted site score — combine criteria without hiding the weights*, keep transparent multi-criteria comparison of candidate field or settlement sites on one declared boundary. Apply $S_{\text{site}} = \text{sum}(w_i \times s_i)$ under that convention. A weighted score is a decision aid, not a natural law; correlated criteria and arbitrary weights can create false precision.

10 — Why this operation

Why this operation. $S_{\text{site}} = \text{sum}(w_i \times s_i)$ answers the *Weighted site score — combine criteria without hiding the weights* question because it represents transparent multi-criteria comparison of candidate field or settlement sites. In this case it yields: The weighted score is 0.755 on a 0-to-1 scale.

11 — Assumptions

Assumptions. Treat the *Weighted site score — combine criteria without hiding the weights* values as one teaching case. For transparent multi-criteria comparison of candidate field or settlement sites, keep a single physical or operational boundary. A weighted score is a decision aid, not a natural law; correlated criteria and arbitrary weights can create false precision.

12 — Unit check

Unit check. Reduce $S_{\text{site}} = \text{sum}(w_i \times s_i)$ for *Weighted site score — combine criteria without hiding the weights*. The required dimension is **dimensionless when weights and scores are dimensionless**. A different dimension invalidates “The weighted score is 0.755 on a 0-to-1 scale.”.

13 — Numerical case

$$w = 0.40, 0.35, 0.25$$

$$s = 0.80, 0.60, 0.90$$

$$S_{\text{site}} = 0.40 \times 0.80 + 0.35 \times 0.60 + 0.25 \times 0.90 = 0.755$$

14 — Why each operation

Why each operation. For *Weighted site score — combine criteria without hiding the weights*, substitute $w = 0.40, 0.35, 0.25$; $s = 0.80, 0.60, 0.90$; $S_{\text{site}} = 0.40 \times 0.80 + 0.35 \times 0.60 + 0.25 \times 0.90 = 0.755$ into $S_{\text{site}} = \text{sum}(w_i \times s_i)$. Then verify the independent statement “The weights sum to 1.00; contributions sum to 0.755.”.

15 — Algebra check

Algebra check. Reverse $S_{\text{site}} = \text{sum}(w_i \times s_i)$ for *Weighted site score — combine criteria without hiding the weights* using “The weights sum to 1.00; contributions sum to 0.755.”. The recovered input should follow “Raising the second score from 0.60 to 0.80 adds $0.35 \times 0.20 = 0.070$ to the total.”. If not, recheck units and boundaries.

16 — Mental estimate

Mental estimate. Round the dominant inputs for *Weighted site score — combine criteria without hiding the weights*. Compare that rough scale with “The weighted score is 0.755 on a 0-to-1 scale.”. If they diverge sharply, inspect $S_{\text{site}} = \text{sum}(w_i \times s_i)$ for units, signs or boundaries.

17 — Interpretation

Interpretation. For *Weighted site score — combine criteria without hiding the weights*, The weighted score is 0.755 on a 0-to-1 scale. Operationally: Publish weights and sensitivity tests so a review board can see why a site wins. The interpretation remains limited by “A weighted score is a decision aid, not a natural law; correlated criteria and arbitrary weights can create false precision.”.

18 — What it does not prove

What it does not prove. *Weighted site score — combine criteria without hiding the weights* cannot support claims outside transparent multi-criteria comparison of candidate field or settlement sites. A weighted score is a decision aid, not a natural law; correlated criteria and arbitrary weights can create false precision. Use the result only to justify: Publish weights and sensitivity tests so a review board can see why a site wins.

19 — Sensitivity or limit case

Raising the second score from 0.60 to 0.80 adds $0.35 \times 0.20 = 0.070$ to the total.

20 — Practice

Guided exercise — Weighted site score — combine criteria without hiding the weights. Using weights 0.5, 0.3, 0.2 and scores 0.7, 0.9, 0.6, calculate the weighted score.

Guided correction — Weighted site score — combine criteria without hiding the weights

1. $S = 0.5 \times 0.7 + 0.3 \times 0.9 + 0.2 \times 0.6 = 0.74$.
2. Then test whether the ranking changes under plausible alternative weights.

Autonomous exercise — Weighted site score — combine criteria without hiding the weights. Build a second case from “Raising the second score from 0.60 to 0.80 adds $0.35 \times 0.20 = 0.070$ to the total.”. Re-evaluate $S_{\text{site}} = \sum(w_i \times s_i)$. Name the changed input. Decide whether “Publish weights and sensitivity tests so a review board can see why a site wins.” still follows.

Autonomous correction — Weighted site score — combine criteria without hiding the weights

For *Weighted site score — combine criteria without hiding the weights*, state the altered case. Preserve **dimensionless when weights and scores are dimensionless**. Match the direction in “Raising the second score from 0.60 to 0.80 adds $0.35 \times 0.20 = 0.070$ to the total.”. Respect “A weighted score is a decision aid, not a natural law; correlated criteria and arbitrary weights can create false precision.”. Finish by retaining or revising: Publish weights and sensitivity tests so a review board can see why a site wins.

21 — Mission decision

Publish weights and sensitivity tests so a review board can see why a site wins.

Relative error — compare a measurement with a reference magnitude

$$e_{\text{rel}} = \text{abs}(x_{\text{meas}} - x_{\text{ref}}) / \text{abs}(x_{\text{ref}})$$

1 — Concrete question

For **Relative error — compare a measurement with a reference magnitude**, how does $e_{\text{rel}} = \text{abs}(x_{\text{meas}} - x_{\text{ref}}) / \text{abs}(x_{\text{ref}})$ inform quality control when the scale of the reference value matters and the operational choice “Use relative error to trigger calibration review when the mission requirement is stated as a percentage tolerance.”?

2 — Intuition without symbols

Intuition. An absolute difference means little without the scale of the reference. Relative error expresses the mismatch as a share of the reference magnitude, allowing measurements of different sizes to be compared more meaningfully.

3 — Quantities first

x_{meas} is measured value; x_{ref} is reference value; e_{rel} is relative error magnitude.

4 — Formula

$$e_{\text{rel}} = \text{abs}(x_{\text{meas}} - x_{\text{ref}}) / \text{abs}(x_{\text{ref}})$$

5 — Read aloud

“ e_{rel} equals absolute x measured minus x reference divided by absolute x reference.”

6 — Symbols

Symbol map for Relative error — compare a measurement with a reference magnitude. x_{meas} is measured value; x_{ref} is reference value; e_{rel} is relative error magnitude.

7 — Pronunciation

Pronunciation. Say $e_{\text{rel}} = \text{abs}(x_{\text{meas}} - x_{\text{ref}}) / \text{abs}(x_{\text{ref}})$. For *Relative error — compare a measurement with a reference magnitude*, use the step-three names tied to quality control when the scale of the reference value matters. Speak each *Relative error — compare a measurement with a reference magnitude* unit with the quantity it measures.

8 — Units

same unit / same unit = dimensionless

9 — Convention

Convention. For *Relative error — compare a measurement with a reference magnitude*, keep quality control when the scale of the reference value matters on one declared boundary. Apply $e_{\text{rel}} = \text{abs}(x_{\text{meas}} - x_{\text{ref}}) / \text{abs}(x_{\text{ref}})$ under that convention. The expression is undefined for $x_{\text{ref}} = 0$ and does not include measurement uncertainty by itself.

10 — Why this operation

Why this operation. $e_{\text{rel}} = \text{abs}(x_{\text{meas}} - x_{\text{ref}}) / \text{abs}(x_{\text{ref}})$ answers the *Relative error — compare a measurement with a reference magnitude* question because it represents quality control when the scale of the reference value matters. In this case it yields: The measurement differs from the reference by 2.0% of the reference magnitude.

11 — Assumptions

Assumptions. Treat the *Relative error — compare a measurement with a reference magnitude* values as one teaching case. For quality control when the scale of the reference value matters, keep a single physical or operational boundary. The expression is undefined for $x_{\text{ref}} = 0$ and does not include measurement uncertainty by itself.

12 — Unit check

Unit check. Reduce $e_{\text{rel}} = \text{abs}(x_{\text{meas}} - x_{\text{ref}}) / \text{abs}(x_{\text{ref}})$ for *Relative error — compare a measurement with a reference magnitude*. The required dimension is $\text{same unit} / \text{same unit} = \text{dimensionless}$. A different dimension invalidates “The measurement differs from the reference by 2.0% of the reference magnitude.”.

13 — Numerical case

$$x_{\text{meas}} = 9.8$$

$$x_{\text{ref}} = 10.0$$

$$e_{\text{rel}} = |9.8 - 10.0| / 10.0 = 0.020 = 2.0\%$$

14 — Why each operation

Why each operation. For *Relative error — compare a measurement with a reference magnitude*, substitute $x_{\text{meas}} = 9.8$; $x_{\text{ref}} = 10.0$; $e_{\text{rel}} = |9.8 - 10.0| / 10.0 = 0.020 = 2.0\%$ into $e_{\text{rel}} = \text{abs}(x_{\text{meas}} - x_{\text{ref}}) / \text{abs}(x_{\text{ref}})$. Then verify the independent statement “2.0% of 10.0 is 0.20, matching the absolute difference.”.

15 — Algebra check

Algebra check. Reverse $e_{\text{rel}} = \text{abs}(x_{\text{meas}} - x_{\text{ref}}) / \text{abs}(x_{\text{ref}})$ for *Relative error — compare a measurement with a reference magnitude* using “2.0% of 10.0 is 0.20, matching the absolute difference.”. The recovered input should follow “A fixed absolute error becomes a larger relative error as the reference magnitude becomes smaller.”. If not, recheck units and boundaries.

16 — Mental estimate

Mental estimate. Round the dominant inputs for *Relative error — compare a measurement with a reference magnitude*. Compare that rough scale with “The measurement differs from the reference by 2.0% of the reference magnitude.”. If they diverge sharply, inspect $e_{\text{rel}} = \text{abs}(x_{\text{meas}} - x_{\text{ref}}) / \text{abs}(x_{\text{ref}})$ for units, signs or boundaries.

17 — Interpretation

Interpretation. For *Relative error — compare a measurement with a reference magnitude*, The measurement differs from the reference by 2.0% of the reference magnitude. Operationally: Use relative error to trigger calibration review when the mission requirement is stated as a percentage tolerance. The interpretation remains limited by “The expression is undefined for $x_{ref} = 0$ and does not include measurement uncertainty by itself.”.

18 — What it does not prove

What it does not prove. *Relative error — compare a measurement with a reference magnitude* cannot support claims outside quality control when the scale of the reference value matters. The expression is undefined for $x_{ref} = 0$ and does not include measurement uncertainty by itself. Use the result only to justify: Use relative error to trigger calibration review when the mission requirement is stated as a percentage tolerance.

19 — Sensitivity or limit case

A fixed absolute error becomes a larger relative error as the reference magnitude becomes smaller.

20 — Practice

Guided exercise — Relative error — compare a measurement with a reference magnitude. A measurement is 48.5 when the reference is 50.0. Calculate relative error.

Guided correction — Relative error — compare a measurement with a reference magnitude

1. $e_{rel} = |48.5 - 50.0| / 50.0 = 1.5 / 50.0 = 0.030 = 3.0\%$.
2. Report uncertainty separately from this point estimate.

Autonomous exercise — Relative error — compare a measurement with a reference magnitude.

Build a second case from “A fixed absolute error becomes a larger relative error as the reference magnitude becomes smaller.”. Re-evaluate $e_{rel} = \text{abs}(x_{meas} - x_{ref}) / \text{abs}(x_{ref})$. Name the changed input. Decide whether “Use relative error to trigger calibration review when the mission requirement is stated as a percentage tolerance.” still follows.

Autonomous correction — Relative error — compare a measurement with a reference magnitude

For *Relative error — compare a measurement with a reference magnitude*, state the altered case. Preserve $\text{same unit} / \text{same unit} = \text{dimensionless}$. Match the direction in “A fixed absolute error becomes a larger relative error as the reference magnitude becomes smaller.”. Respect “The expression is undefined for $x_{ref} = 0$ and does not include measurement uncertainty by itself.”. Finish by retaining or revising: Use relative error to trigger calibration review when the mission requirement is stated as a percentage tolerance.

21 — Mission decision

Use relative error to trigger calibration review when the mission requirement is stated as a percentage tolerance.