From an everyday device to professional instrumentation. A framework for Portable Geoscience Learning Infrastructure and its illustrative application to ITA ARANDU MS

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Abstract

Geoscience education depends on practices that connect classroom learning with field settings: observing, locating, measuring, recording, comparing evidence, reasoning under uncertainty, and constructing interpretations. Digital fieldwork allows some of these practices to be undertaken with mobile devices, yet digital convenience, instrumental accuracy, and learning are not equivalent. This paper develops Portable Geoscience Learning Infrastructure (PGLI), a conceptual framework for analyzing digital resources carried by learners that sustain continuity across preparation, fieldwork, and synthesis while preserving learner authorship of field records, epistemic transparency, progression to professional instrumentation, and context-sensitive data governance. The framework was derived through a problem-oriented thematic synthesis of literature on geoscience cognition and competencies, field-based and situated learning, digital geology and mobile learning, uncertainty and epistemic practices, learner participation, and data governance. Six design principles are proposed: portability and reduced dependence on additional infrastructure; continuity across settings and local-first resilience; disciplinary practice and learner authorship of field records; epistemic transparency; progression to professional instrumentation and awareness of limitations; and context-sensitive ethical and territorial data governance. ITA ARANDU MS, a mobile-first Progressive Web App developed in Mato Grosso do Sul, Brazil, is used as an illustrative application rather than as evidence of effectiveness. An illustrative contrastive application to published systems yields distinct analytical profiles without ranking quality or claiming external validation. PGLI offers operational criteria and explicit failure conditions for examining when a mobile environment functions as portable educational infrastructure and what evidence is still needed to evaluate its effects in use.

Keywords: geoscience education; fieldwork; mobile learning; epistemic transparency; data governance.

1. Introduction

A defining feature of geoscience education is that much disciplinary knowledge develops through the interplay of place, observation, representation, and inference. Geoscientists work with incomplete records, spatially distributed objects, scales ranging from microscopic to continental, and processes that cannot be observed in full within human timescales. Learning geoscience therefore requires more than memorizing concepts. Students must learn to produce and evaluate evidence, represent spatial relationships, distinguish observation from interpretation, and judge when an explanation is supported or constrained by the available data (Kastens et al., 2009; Liben & Titus, 2012; Mogk & Goodwin, 2012; Mosher & Keane, 2021).

Over the past two decades, these practices have become increasingly digital. Smartphones and tablets combine cameras, geolocation, orientation sensors, storage, and processing capacity; specialized platforms structure field stations, geological relationships, maps, and models; and web applications extend access to cartography and content within the territory itself. Smart Compass-Clinometer, FieldMove, StraboSpot, Flyover Country, Svalbox, IdroGEO, GeoWeb Semeru, and KMapper represent distinct trajectories within this transformation (Lee et al., 2013; Walker et al., 2019; Lundmark et al., 2020; Loeffler et al., 2021; Senger et al., 2021; Iadanza et al., 2021; Bachri et al., 2023; Yeon et al., 2026). These precedents make any claim of novelty based solely on the use of smartphones, sensors, Progressive Web Apps (PWAs), or offline operation unproductive.

The educational problem lies elsewhere. Infrastructure for field learning is often conceived as something located at the university, in a laboratory, or within the set of equipment mobilized for a formal field exercise. Yet students continue to encounter landscapes, maps, outcrops, road cuts, rural properties, and environmental problems outside those scheduled moments. If part of the learning infrastructure can accompany learners on a device they already carry, opportunities for observation, documentation, and questioning can persist between formal activities. This does not mean that a smartphone is equivalent to a validated geological compass, a precision GNSS receiver, a seismometer, a magnetometer, or a laboratory. The question is whether an everyday device can sustain a portable layer of disciplinary practice before and alongside those resources.

This question is particularly relevant in geographically extensive settings with variable infrastructure. Mato Grosso do Sul covers more than 357,000 km² and has a low population density (IBGE, 2025), while encompassing substantial geological, hydrogeological, and geomorphological diversity. The state has important official cartography, surveys, and information systems, but these sources differ in scale, purpose, and level of detail (Lacerda Filho et al., 2006;

Abreu et al., 2024). At the same time, the Federal University of Mato Grosso do Sul has approved a Geological Engineering degree program in Campo Grande, with the first intake planned for 2027 (UFMS, 2025, 2026). This creates an appropriate moment to ask not only what should be taught, but also what infrastructure can support geoscience practices distributed across the state's extensive field settings from the early years of training.

This paper proposes the concept of Portable Geoscience Learning Infrastructure (PGLI). The construct is deliberately prescriptive and design-oriented: it does not seek to explain learning causally or establish a universal and sufficient set of resources. Its purpose is to organize operational questions for settings in which part of the geoscience learning infrastructure travels with students between university and field settings under variable connectivity, equipment availability, and governance regimes. The framework is derived from literature external to ITA ARANDU and only then applied to the system, reducing circularity between development and analysis. Learner agency is treated as a possible future educational outcome; at the design level, the inspectable principle is learner authorship of field records and interpretations.

Three research questions guide the study. (1) Which operational principles distinguish Portable Geoscience Learning Infrastructure from a generic collection of mobile resources? (2) How can these principles guide concrete design decisions - offline continuity, separation of field observation from cartographic context, presentation of sensor readings, learner authorship of field records, and data governance - without conflating implemented functionality with demonstrated learning? (3) Does applying the framework yield distinct analytical profiles when examining digital geoscience systems with different purposes, and which epistemic, instrumental, and ethical limits remain explicit?

2. Context: place, geoscience education, and digital access

2.1. Mato Grosso do Sul as a context for place-based learning

Mato Grosso do Sul serves here as a context for framework construction and application, not as an argument for exceptionalism. Its large territorial extent brings together markedly different geological and geomorphological settings within one state, including Phanerozoic cover of the Paraná Basin, Cenozoic deposits of the Pantanal, and Precambrian terranes in the west and southwest. The statewide 1:1,000,000 geological synthesis and the hydrogeological map published in 2024 provide important regional references, but they also illustrate a basic instructional principle: a regional source does not replace local observation, and lack of cartographic detail does not imply the absence of a geological phenomenon (Lacerda Filho et al., 2006; Abreu et al., 2024). This context supports a place-based approach. Place-based geoscience education uses local landscapes, problems, and histories as entry points to transferable concepts without reducing education to regionalism (Semken & Freeman, 2008; Semken et al., 2017). For an emerging Geological Engineering program, the state itself can simultaneously serve as an object of study, a source of authentic problems, and a setting in which students learn to compare scales, provenance, and levels of confidence and uncertainty. Portability matters precisely because the place of learning does not always coincide with the location of university infrastructure.

2.2. The smartphone as a starting point, not an assumption of inclusion

A mobile-first choice is supported by the Brazilian digital-access context, but it must be interpreted cautiously. In TIC Educação 2024, 97% of student Internet users reported using a mobile phone to access the Internet, compared with 48% using a laptop or Chromebook and 39% using a desktop computer. In TIC Domicílios 2025, 36% of Internet users in Brazil's Central-West region accessed the Internet exclusively by mobile phone (NIC.br, 2024, 2025). These indicators do not describe the future UFMS cohort and do not justify assuming that every student owns an adequate device.

They support only a design decision: requiring a personal computer as the primary access device may create an additional requirement that a mobile-first environment seeks to avoid.

Nor is the smartphone assumed to be free, homogeneous, or universal. Devices differ in sensors, battery life, storage, permissions, browser support, positioning accuracy, and camera quality. Accordingly, the reduced-dependency rationale used here refers to lowering additional hardware requirements for selected practices when a learner already has a compatible device. Institutional loan programs, accessibility, connectivity, field safety, and access to professional equipment remain essential educational responsibilities, consistent with broader concerns about barriers to undergraduate geoscience fieldwork (Giles et al., 2020).

3. Conceptual foundations

3.1. Geoscience practices and competencies

Vision and Change in the Geosciences synthesizes broad expectations for undergraduate education, including critical thinking, problem solving, data integration, spatial and temporal reasoning, working with uncertainty, technological competence, and field experience (Mosher & Keane, 2021). Kastens et al. (2009) and Liben and Titus (2012) show that geoscience reasoning depends on coordinating observations, representations, scale, and spatiotemporal processes. Mogk and Goodwin (2012) emphasize fieldwork as a setting in which observation, navigation, recording, communication, and interpretation bring students closer to professional practice.

The framework developed here does not attempt to reproduce the full scope of geoscientist preparation. Its domain is narrower: field, pre-field, and post-field practices that can be supported by portable infrastructure. Within this domain, eight dimensions define the analytical scope: geological observation; spatial and scale reasoning; measurement and instrumental understanding; evidence traceability; reasoning under uncertainty; interpretation and construction of explanations; inquiry and formulation of new questions; and digital field competence. These are practice dimensions relevant to the problem under study, not an exhaustive list of professional competencies.

3.2. Fieldwork, place, and continuity of learning

Fieldwork does not begin when the student reaches the outcrop. Orion (1993) and Orion and Hofstein (1994) demonstrated the importance of preparation and novelty space, that is, the cognitive, geographic, and psychological load associated with working in an unfamiliar environment. Digital tools can reduce part of this novelty by supporting prior reconnaissance and task organization, but they can also introduce new dependencies and distractions. Portable infrastructure must therefore connect preparation, field observation, and later synthesis rather than turn the smartphone into a self-contained screen.

Place-based literature complements this argument by shifting attention from the device to the relationship between learner and place. The educational value of a mobile map or georeferenced field station lies not only in accelerating record creation but also in enabling students to revisit a site, relate evidence across scales, and compare their observations with existing sources (Semken et al., 2017). Continuity across settings is therefore more than network connectivity: it is continuity of the geoscience problem across different moments of learning.

Situated learning extends this view by treating knowledge as inseparable from the activities, artifacts, and social practices through which it is produced and used (Brown et al., 1989; Lave & Wenger, 1991). For the present framework, this does not mean assuming that being in the field automatically produces learning. It means recognizing that portable tools can bring students closer to authentic practice when they support disciplinary practices in the contexts where observations and decisions must be made. PGLI is therefore not a theory of situated learning; it specifies properties of infrastructure that may support such participation without replacing instructor guidance, collaboration, or membership in a community of practice.

3.3. Digital geology, mobile learning, and limits of instrumentation

The digital-geology literature documents both clear benefits and important limitations (Lee et al., 2018). Lee et al. (2013) demonstrated the integration of compass-clinometer functionality and analysis on a smartphone. Allmendinger et al. (2017) and Novakova and Pavlis (2017) assessed accuracy and best practices for structural measurements using mobile devices, showing that hardware, interference, and procedure matter. Tavani et al. (2022) position the smartphone within the digital transition of fieldwork, whereas StraboSpot structures observations and geological relationships with strong attention to provenance (Walker et al., 2019).

In educational settings, Marçal et al. (2017) documented mobile learning in a geology field class in Brazil. Lundmark et al. (2020) showed that students adopted FieldMove rapidly, but cautioned that the professional appearance of digital products may increase confidence without a corresponding increase in understanding. Svalbox demonstrated how regional geology, digital data, and authentic activities can be combined without replacing real fieldwork (Senger et al., 2021). KMapper more directly connected stages of geological surveying with digital competence (Yeon et al., 2026). Together, these studies support an important conclusion: the question is not whether a phone can perform a task, but how its use is designed to preserve reasoning, validation, and transition to professional practice.

3.4. Uncertainty, epistemic practices, and record authorship

Uncertainty is constitutive of geoscience practice. Bateman et al. (2022) showed that uncertainty can be taught explicitly in a field course and incorporated by students into geological arguments. Such explicit treatment is particularly important in digital interfaces, where numbers, maps, and classifications can acquire an appearance of precision beyond what the evidence supports. Educational infrastructure that keeps source, scale, method, and uncertainty inspectable does not eliminate uncertainty; it makes uncertainty a visible part of disciplinary work and leaves space for learners to question, compare, and revise their interpretations rather than receiving geological conclusions as fixed outputs. In this sense, the framework is also consistent with Freire's (1996) emphasis on education as a process in which learners develop autonomy through inquiry and critical engagement with the world rather than through the passive reception of ready-made knowledge.

Literature on participation in scientific practices provides a necessary distinction between design conditions and learner outcomes. LaDue et al. (2022) include an agentic dimension in their model of active learning in geoscience, and Stroupe (2018) discusses epistemic agency as participation in knowledge production. PGLI does not treat "agency" as an observable interface attribute. At the framework level, the inspectable principle is learner authorship of field records: learners should be able to initiate observations, select evidence, record interpretations, revise them when new evidence emerges, and retain control over how those decisions are documented without the system automatically replacing those operations. This conception of authorship is compatible with Freire's (1996) pedagogy of autonomy because the digital tool does not position the learner as a recipient of predetermined answers. Instead, it supports a relationship in which observation, questioning, interpretation, and revision remain activities performed by the learner in relation to the field and the problem being investigated. Whether these design conditions foster epistemic agency or greater learner autonomy is, however, an empirical question that must be investigated with students.

4. Framework development

4.1. Conceptual construction approach

This is a conceptual framework study. It is neither an effectiveness study, a systematic review, nor a design-based research study. Framework construction was informed by Jabareen's (2009) approach to conceptual-framework analysis and by recent precedents in the Journal of Geoscience Education in which interdisciplinary literature is synthesized to formulate models applicable to existing practices or programs (LaDue et al., 2022; Manning & LaDue, 2025). We used a problem-oriented thematic synthesis to identify recurring tensions, compare constructs, and translate them into principles with observable criteria and failure conditions. The analytical sequence was: problem delimitation; thematic grouping of relevant traditions; identification of recurring tensions; formulation of principles; definition of indicators and failure conditions; illustrative application; and contrastive application to systems documented in the literature.

To reduce arbitrariness in moving from literature to principles, a principle was retained only when it met four criteria simultaneously: (a) it addressed a problem or tension supported by more than one relevant source; (b) it could be expressed as an observable design decision; (c) it could be associated with at least one identifiable failure condition; and (d) it was not reducible to another principle already formulated. The synthesis does not claim thematic saturation or bibliographic exhaustiveness. These criteria make the derivation traceable but do not replace external validation; other researchers may regroup, reject, or add principles.

Literature selection was purposive and theory-driven rather than exhaustive. Priority was given to synthesis work in geoscience education, empirical studies directly related to digital fieldwork, papers on accuracy and uncertainty, and systems that established relevant functional precedents. The aim was not to estimate the frequency of findings in the literature, but to make explicit the reasoning chain connecting literature, constructs, and framework principles. Table 1 summarizes this derivation chain.

Literature family	Guiding references	Recurring problem	Derived principles
Geoscience competencies and cognition	Kastens et al. (2009); Liben & Titus (2012); Mogk & Goodwin (2012); Mosher & Keane (2021)	Disciplinary practices require observation, scale, evidence integration, and inference.	P3, P4, P5
Fieldwork, place, and situated learning	Orion (1993); Orion & Hofstein (1994); Semken et al. (2017); Brown et al. (1989); Lave & Wenger (1991)	Learning spans preparation, authentic activity, territory, and synthesis.	P2, P3

Literature family	Guiding references	Recurring problem	Derived principles
Digital geology and mobile learning	Lee et al. (2013); Lundmark et al. (2020); Walker et al. (2019); Senger et al. (2021)	Portability expands recording capacity, but convenience is not equivalent to understanding or accuracy.	P1, P2, P5
Uncertainty and epistemic practices	Bateman et al. (2022); Wilson et al. (2019)	Source, scale, method, and uncertainty need to remain inspectable.	P4
Participation, authorship, and active learning	LaDue et al. (2022); Stroupe (2018)	Learners need to participate in producing the record; agency is an outcome to investigate, not an interface property.	P3
Digital access and infrastructure	NIC.br (2024, 2025); Iadanza et al. (2021); Bachri et al. (2023)	Reduced dependence on additional infrastructure and resilient operation matter in settings with variable access.	P1, P2
Geoethics and data governance	Carroll et al. (2020); Peppoloni & Di Capua (2016)	Technical capacity to record does not, by itself, establish legitimacy to collect, geolocate, or share data.	P6

Table 1. Derivation chain for the framework. The synthesis is thematic and problem-oriented rather than an exhaustive systematic review.

4.2. Definition and domain of applicability

Portable Geoscience Learning Infrastructure is defined here as a configuration of digital resources carried by learners that sustains continuity of geoscience practice across preparation, fieldwork, and synthesis while reducing dependence on additional hardware and connectivity and preserving epistemic transparency and an explicit progression to professional instrumentation and workflows. PGLI is a prescriptive design framework. It organizes questions for the development and analysis of learning environments; by itself, it does not predict learning gains.

The domain of applicability is higher-education geoscience and, potentially, other forms of field-based education in which learners move across settings and available infrastructure varies. The framework is not necessary for every educational situation. A highly equipped fixed laboratory may not need a portable layer to meet its objectives. Likewise, a mobile application that only presents content may be useful without constituting PGLI. The construct becomes relevant when portability is expected to sustain disciplinary practice and continuity across settings.

4.3. Six design principles and an inspection rubric

Table 2 presents the six principles as an inspection rubric, linking each design requirement to a failure condition and an observable detection procedure.

Principle	Design requirement	Failure condition	How to detect it in the design
P1. Portability and reduced dependence on additional infrastructure	The core workflow runs on the device carried by the learner and reduces additional dependencies for selected practices.	The central task requires a fixed computer, permanent additional hardware, or an installation incompatible with the field device.	List mandatory dependencies and execute the essential workflow using only the mobile device.
P2. Continuity across settings and local-first resilience	Preparation, consultation, recording, and retrieval span classroom, field, and synthesis under variable connectivity.	Loss of network access prevents recording, retrieving, or preserving the essential activity.	Run a no-network field test and verify persistence, retrieval, and later export.
P3. Disciplinary practice and learner authorship of field records	The learner initiates recognizable disciplinary geoscience practices and retains authorship over observation, evidence selection, and interpretation.	The interface reduces activity to consuming answers or automatically fills in the central inference.	Inspect which fields are produced by the student and which are inferred, populated, or decided by the system.
P4. Epistemic transparency	Source, scale, method, precision, uncertainty, and the distinction among observation, measurement, derived product, and interpretation remain inspectable.	The interface merges cartographic context with observation, hides provenance, or presents a derived result as an unqualified fact.	Audit the data-to-interface flow and verify that origin, scale, method, and epistemic status remain visible.
P5. Progression to professional instrumentation and awareness of limitations	The system makes explicit when a practice is formative or auxiliary and when it requires calibration, professional equipment, laboratory work, or a specialized protocol.	A consumer device is presented as broadly equivalent to professional instrumentation or as the endpoint of training.	Review labels, warnings, metadata, and proposed transitions toward professional instrumentation and workflows.
P6. Context-sensitive ethical and territorial data governance	Collection, storage, and sharing are aligned with the context, preserving consent, user/community control, territorial sensitivity, and limits on collection or sharing.	Technical capability expands collection or export without considering context-specific requirements for authorization, sensitivity, sovereignty, or control.	Review permissions, storage location, export options, sensitivity marking, and consent/governance protocols.

Table 2. PGLI inspection rubric. The principles provide observable criteria and failure conditions; they are neither a psychometric scale nor presented as universally necessary or sufficient.

Figure 1 summarizes how the six principles connect portability across settings with progression toward professional practice.

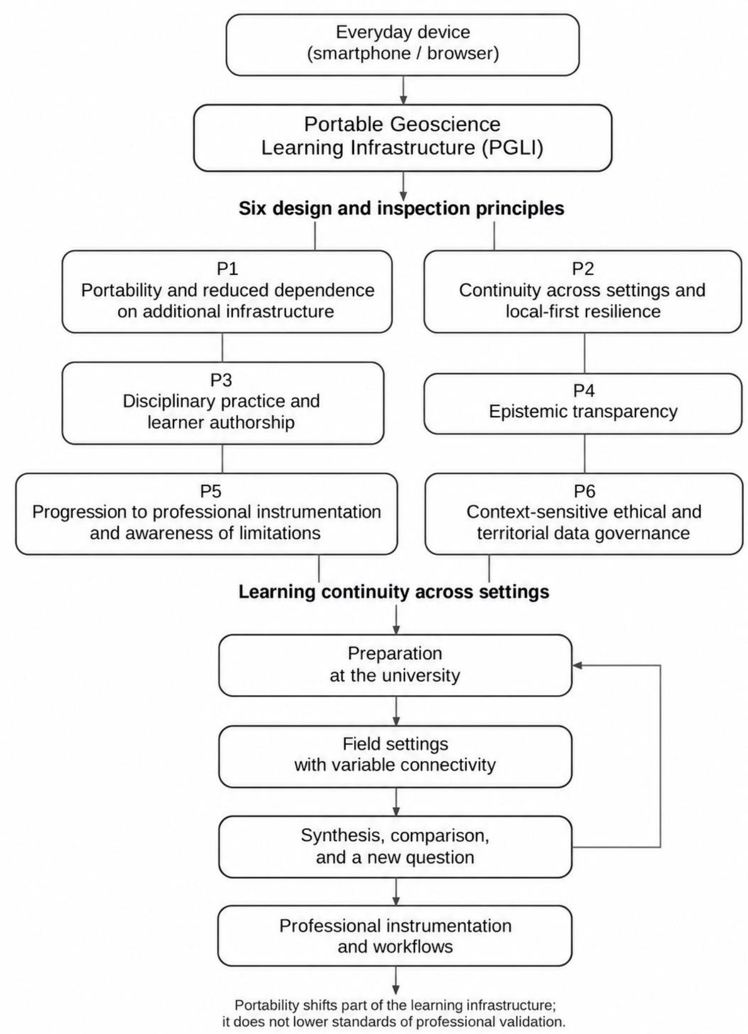


Figure 1. Portable Geoscience Learning Infrastructure (PGLI) framework. Portability shifts part of the learning infrastructure across university and field settings, but it does not lower standards of professional validation, epistemic transparency, or ethical governance.

4.4. Relationship to existing frameworks

PGLI does not replace broader pedagogical frameworks and does not claim to explain the full teaching and learning process. TPACK describes the knowledge that teachers integrate across technology, pedagogy, and content (Mishra & Koehler, 2006). Geo-STEM Learning Ecosystems examines relationships among people, institutions, places, and processes within learning communities (Manning & LaDue, 2025). Mobile learning and situated learning help explain mobility, context, and participation in authentic practices (Brown et al., 1989; Lave & Wenger, 1991; Marçal et al., 2017). PGLI operates at a different analytical scale: it asks which properties the digital layer carried by the learner must preserve as geoscience practice moves across settings. The distinction must lead to decisions, not merely vocabulary. Table 3 presents four scenarios in which PGLI provides a specific operational criterion. This does not mean that the other frameworks cannot address these situations; rather, these issues are not their primary analytical object. The proposed contribution is to make portability, the epistemic status of evidence, transition toward professional instrumentation, and territorial data governance explicit dimensions for inspecting mobile geoscience infrastructure.

Design decision	TPACK	Geo-STEM / learning ecosystems	Mobile / situated learning	PGLI-specific criterion
Field activity without network connectivity	Assesses technology-pedagogy-content fit but does not prescribe offline architecture.	Examines ecosystem relationships and access to resources.	Values learning in context without defining a technical persistence requirement.	P2 requires essential recording and retrieval to survive loss of network connectivity.
A regional map suggests the local geological unit	Can inform a pedagogical choice but does not define the epistemic status of interface fields.	Not a primary focus at the ecosystem scale.	Authentic practice encourages learners to compare mapped context with field evidence but does not specify an interface rule.	P4 prevents cartographic context from being recorded as direct field observation and requires visible provenance and scale.
A phone sensor produces a reading	Can address the appropriateness of technology to content.	Can situate professional resources within the broader learning ecosystem.	Can support authentic practice but does not specify a transition to calibrated professional measurement.	P5 requires the reading to be labeled as auxiliary, its limitations stated, and the transition to professional instrumentation made explicit.
Geolocated recording in a sensitive territory	Can integrate ethics into pedagogical decision making without a dedicated territorial dimension.	Can include communities and power relationships at the systemic level.	Situated practice and community are central, but data governance is not a universal technical requirement.	P6 requires inspection of consent, sensitivity, control, storage, and export.

Table 3. Operational differentiation of PGLI from broader frameworks. The comparison distinguishes analytical objects; it is not a ranking and does not claim that the other frameworks exclude these issues.

5. Illustrative application to ITA ARANDU MS

5.1. Role of the application in this paper

ITA ARANDU MS is used as an illustrative application of the framework, not as evidence of external validity. This distinction is central because the authors also participate in the system's development and scientific curation. The case is used to ask whether the principles are sufficiently clear to guide an inspection and to classify design correspondence as strong, partial, or not evidenced. The conclusion is neither that the software 'validates' the framework nor that the framework demonstrates learning.

The application examines version V38.4.59-FIELD-ROBUSTNESS-20260910. Future or merely planned functions are not used as evidence. The focus is not software architecture, performance, or completeness of the geoscience catalog, but the educational function of technical elements that are already implemented: browser/PWA execution, local storage, offline preparation, station-based field notebook, geolocation, multimodal recording, sensor-assisted tools, learning missions, export, and explicit presentation of source, scale, and evidential status.

5.2. Technical operation as educational infrastructure

The PWA approach is educationally relevant because it reduces dependence on app-store distribution and allows the same environment to run in compatible browsers. Local storage matters because a field station or note can persist on the device; an offline package matters because fieldwork cannot depend on continuous network coverage; geolocation and the camera matter because they connect observations to place and documentation; and export matters because it gives students an artifact that can be transferred to GIS, a report, or subsequent analysis. None of these functions is, by itself, a pedagogical innovation. The argument is that together they shift part of the learning infrastructure from a fixed location to a capacity carried by the learner.

In this sense, portability changes the spatial distribution of learning infrastructure. Part of the learning environment can accompany students to a road cut, outcrop, farm or other rural property, rural school, or other observation site, even when the university is far away. The educational consequence that can be inspected at the design level is continuity of practice; autonomy, agency, and learning outcomes associated with that continuity remain empirical questions.

5.3. Application of the six principles

Table 4 applies the six PGLI principles to the implemented version of ITA ARANDU MS.

Principle	Diagnosis	Design evidence	Limit of the evidence
P1. Portability / reduced infrastructure dependence	Strong at the design level	Core workflow is mobile-first and browser-based; field notebook, map, media, and export are accessible on the device.	Does not demonstrate that all students own compatible hardware.
P2. Continuity / local-first	Strong at the design level	Local persistence, offline preparation, and continuity across reconnaissance, fieldwork, and post-field synthesis.	Persistence depends on browser behavior, storage, and backup practices.
P3. Disciplinary practice / field-record authorship	Strong at the design level	The student creates a station, selects descriptors, records observations and interpretations, and controls export.	Does not demonstrate agency, motivation, or the quality of records produced in actual use.
P4. Epistemic transparency	Strong at the design level	Separation among cartographic context, observation, measurement, and interpretation; source, scale, precision, and uncertainty states are made visible.	It remains necessary to test whether students notice and use these distinctions.
P5. Progression to professional instrumentation	Partial	Warnings about limitations, method recording, and distinction between auxiliary sensors and professional instruments.	Transfer to a Brunton compass, GNSS, geophysical, or laboratory workflows has not been evaluated.
P6. Context-sensitive ethical / territorial data governance	Partial	Local storage and user-initiated export reduce automatic extraction; responsibility and governance are made conceptually explicit.	Granular consent controls, territorial-sensitivity classification, and community protocols are not yet embedded across all workflows.

Table 4. Illustrative application of PGLI to ITA ARANDU MS. 'Strong,' 'partial,' and 'not evidenced' describe design correspondence according to explicit criteria, not educational effectiveness.

Three categories were defined in advance for this application: 'strong at the design level' when the requirement and its detection indicator are observable in the version analyzed and no contradictory behavior is observed in the inspected workflow; 'partial' when only part of the requirement is implemented, when it depends on an external condition, or when evidence of use is required; and 'not evidenced' when the version or documentation does not allow the principle to be verified. The classification was performed by the authors and has not yet been independently assessed for inter-rater agreement.

5.4. Dimensions of geoscience practice supported by the design

Table 5 maps the implemented environment onto the eight practice dimensions defined in Section 3.1.

Practice dimension	Opportunity in ITA	Correspondence	Safeguard / limit
Geological observation	Station description, photography, sketching, and notes	Strong	Observation remains separate from interpretation.
Spatial and scale reasoning	Geolocation, UTM, maps, and scale comparison	Strong	Regional cartography is not converted into a local field description.
Measurement and instrumental understanding	Orientation, inclination, and auxiliary sensors	Partial	Hardware and calibration vary; training is not equivalent to professional metrology.
Evidence traceability	Source, method, IDs, media, and export	Strong	A derived product is not treated as a primary observation.
Reasoning under uncertainty	Precision, coverage, unknown states, and limitations	Strong at the design level	Effective use of uncertainty in arguments still needs to be studied.
Interpretation and explanation	A separate hypothesis/interpretation field after recording	Partial	Interface separation does not guarantee the quality of an explanation.
Inquiry and new questions	Missions and question formulation around knowledge gaps	Partial	There is not yet evidence that students formulate better questions.
Digital field competence	Offline operation, field notebook, media, and structured export	Strong	Does not represent the full range of digital competence required in professional practice.

Table 5. Eight practice dimensions relevant to the scope of this study. The table is not a rubric of student proficiency.

Figure 2 summarizes the geoscience practice cycle implemented in Modo Aprender ('Learning Mode') and the epistemic checks that remain active across the workflow.

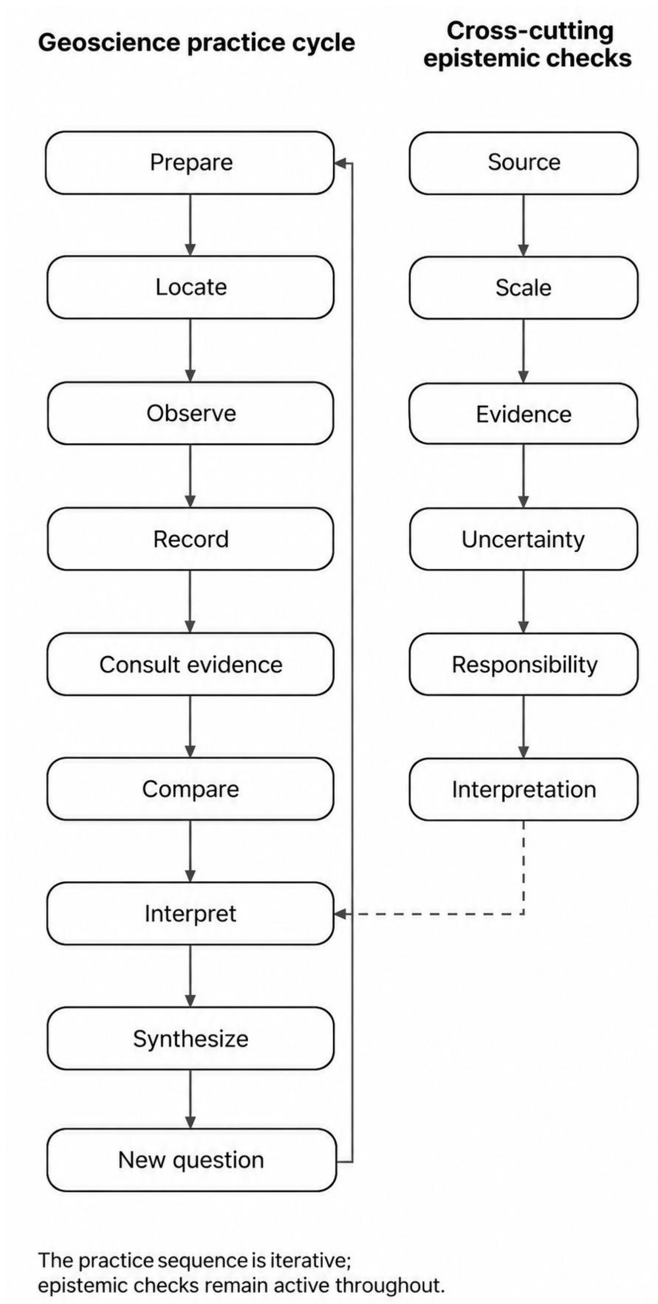
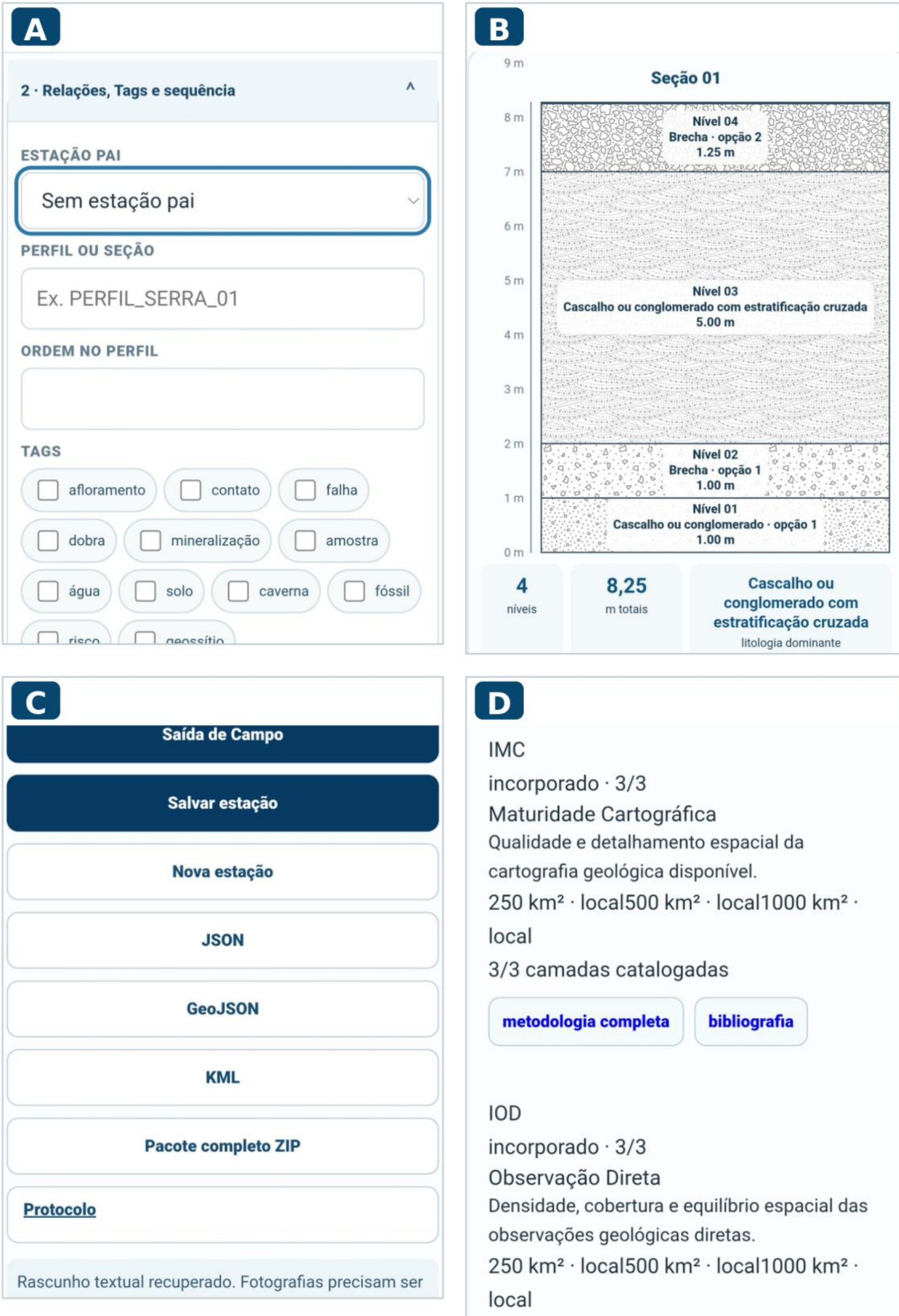


Figure 2. Geoscience practice cycle implemented in Modo Aprender ('Learning Mode'). The left-hand sequence connects preparation, location, observation, recording, evidence consultation, comparison, interpretation, synthesis, and new questions. The right-hand column represents cross-cutting epistemic checks - source, scale, evidence, uncertainty, responsibility, and interpretation - that remain active throughout the workflow. Conceptual content was developed and verified by the authors.

Figure 3 brings together four visual examples from the illustrative application. The purpose is not to demonstrate learning, but to make visible how portable infrastructure is materialized across distinct practices: structured recording of field observations and relationships; construction of a stratigraphic representation; local persistence and export of records; and explicit access to the methodology and bibliography associated with analytical products. Taken together, the panels show that portability is not a single tool but functional continuity across recording, representing, preserving, and interrogating geoscience evidence. Constructing representations, such as a stratigraphic column, is treated as a practice spanning digital field competence and interpretation; the existence of the representation is not taken as evidence of understanding.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Nível 01
Cascalho ou conglomerado · opção 1
1.00 m
4
níveis
8,25
m totais
Cascalho ou conglomerado com estratificação cruzada
litologia dominante
C
Saída de Campo
Salvar estação
Nova estação
JSON
GeoJSON
KML
Pacote completo ZIP
Protocolo
Rascunho textual recuperado. Fotografias precisam ser
D
IMC
incorporado · 3/3
Maturidade Cartográfica
Qualidade e detalhamento espacial da cartografia geológica disponível.
250 km² · local500 km² · local1000 km² · local
3/3 camadas catalogadas
metodologia completa
bibliografia
IOD
incorporado · 3/3
Observação Direta
Densidade, cobertura e equilíbrio espacial das observações geológicas diretas.
250 km² · local500 km² · local1000 km² · local

336

Figure 3. Illustrative components of PGLI in ITA ARANDU MS. (A) Structured geological field station, primarily related to P3 (disciplinary practice and learner authorship of field records); (B) construction of a stratigraphic column, illustrating the transformation of records into a disciplinary representation without constituting evidence of understanding; (C) local persistence and export, associated with P2 (continuity across settings); (D) access to methodology and bibliography within the analytical engine, associated with P4 (epistemic transparency). The panels illustrate design properties; they do not demonstrate learning, actual agency, or instrumental validity. A single component may engage more than one principle; the associations shown are predominant rather than exclusive.

5.5. From an everyday device to professional instrumentation

Progression to professional instrumentation is the principle that prevents portability from being interpreted as substitution. A student can practice measuring and interpreting azimuth and inclination using an embedded sensor; compare readings, record method, and observe interference; work with latitude, longitude, UTM coordinates, and reported accuracy; and explore accelerometer or magnetometer signals. These activities are designed to provide opportunities for familiarization and practice with quantities, procedures, and quality criteria before specialized instrumentation is used. However, tasks that require calibrated accuracy, formal calibration, or a metrological protocol must transition to the appropriate instrument. Table 6 makes this transition explicit across six domains.

Domain	Portable practice	Professional practice / instrumentation	Intended learning purpose
Structural orientation	Azimuth, inclination, trend/plunge, repetition, and recording	Validated compass/clinometer, interference control, and precision procedures	Understand the measured quantity, procedure, and quality-control requirements.
Positioning	Latitude/longitude, UTM, reported accuracy, and relationship to map	Precision/differential GNSS when required by the problem	Distinguish approximate location from survey-grade requirements.
Magnetic field	Explore magnetometer response and interference	Calibrated magnetometry and geophysical protocols	Distinguish exploratory demonstration from professional geophysical acquisition.
Visual recording	Photography, scale, metadata, sketching, and context	Microscopy, petrography, and specialized documentation	Learn to document before interpreting.
Motion and signals	Explore accelerometer response and signal principles	Seismometers and calibrated quantitative acquisition	Distinguish a physical phenomenon from validated scientific measurement.
Data organization	Field notebook, stations, samples, and export	GIS, institutional databases, and laboratory/professional workflows	Transfer documentation standards to more complex environments.

Table 6. Progression from portable practice to professional practice and instrumentation. The transition from portable to professional practice is central to the framework.

5.6. Illustrative contrastive application and analytical differentiation

To examine whether PGLI offers analytical distinctions beyond a favorable description of ITA ARANDU, we applied the framework illustratively and contrastively to three systems documented in the literature. The analysis is limited to what the cited studies make explicit; 'not evidenced' does not mean that a platform lacks the characteristic, and 'outside scope' is not a deficiency. The purpose is to observe whether the principles yield distinct analytical profiles for different architectures and educational purposes without turning them into a ranking or claiming discriminant validity. The resulting contrastive profiles are summarized in Table 7.

System / study	Principles evidenced in the source	Partial / not evidenced / outside scope	PGLI diagnostic reading
FieldMove in Lundmark et al. (2020)	P1 and P3 are clearly evidenced; P5 appears in the instructional sequence combining traditional and digital methods.	P2, P4, and P6 are not central verifiable objects in the cited study.	Strong profile in mapping and disciplinary practice and digital-to-professional transition; PGLI indicates that local-first continuity, epistemic transparency, and governance would require additional evidence.
Svalbox / AG222 in Senger et al. (2021)	P2 and P3 are strongly supported by preparation, data integration, and authentic tasks; P5 is explicit in the complementarity between digital resources and real fieldwork.	P1 is partial because the study does not define reduced additional dependencies in a mobile environment as a central requirement; P4 is partial; P6 is not a focus of the paper.	Profile centered on regional infrastructure and authentic learning, distinct from PGLI's portable/local-first emphasis.
Sedimentary Rock! in Kitazawa et al. (2026)	P1 is compatible with browser execution on computers, smartphones, and tablets; P3 appears in creation/editing of a stratigraphic column.	P2, P4, P5, and P6 are largely outside the stated purpose of the application and study.	Shows that a useful educational web application may not constitute a complete PGLI; the framework describes function, not quality.
ITA ARANDU MS (illustrative application)	P1-P4 show strong correspondence at the design level.	P5 and P6 are partial; educational effects have not been measured.	Displays a profile oriented toward mobile continuity, epistemic transparency, and authorship, while revealing real gaps in validated progression and operational governance.

Table 7. Illustrative contrastive application of PGLI to systems described in the literature. Categories reflect only what is documented in the cited sources and do not constitute a quality assessment of the platforms or external validation of the framework.

6. Discussion

6.1. What the framework adds to the literature

The contribution of PGLI is not to establish that smartphones are useful in education or to propose a causal theory of learning. Its contribution is to offer a different unit of analysis: the digital infrastructure carried by the learner as geoscience practice moves across settings, connectivity conditions, evidence sources, and levels of instrumentation. Table 3 shows how this focus produces explicit design decisions, and Table 7 shows that applying the framework to valuable systems can yield different PGLI profiles depending on their purposes and documentation.

At this stage, the framework's capacity for analytical differentiation is therefore its main theoretical claim. A system may be mobile and educational without prioritizing offline continuity; it may support authentic practice without making epistemic provenance an interface requirement; it may be excellent for visualization without intending to bridge toward professional instrumentation. PGLI makes these differences explicit without claiming discriminant validity at this stage. This allows educators to judge whether the framework is relevant to the problem they face and where it should be modified or rejected.

6.2. Learner authorship of field records and agency as an outcome hypothesis

Learner authorship of field records is treated as a design property: a student can initiate a field station, choose descriptors, produce observations, record an interpretation, and decide when to export the artifact. Agency, by contrast, is an outcome concerning participation and epistemic control that cannot be inferred from this architecture. PGLI therefore does not score 'agency.' It identifies whether the interface preserves or removes disciplinary decisions that would be necessary for agentic participation to be possible. Future studies should examine whether students actually exercise this possibility, to what degree, and with what quality.

The same caution applies to equity. A PWA does not correct digital inequality, and a smartphone does not eliminate the costs of travel, safety, connectivity, or instrumentation. Mobile-first design is a strategy for reducing additional requirements, not a complete inclusion policy. If a class includes students without compatible devices, an equitable implementation must include institutional loan programs or equivalent alternatives. Responsibility for equity remains institutional.

6.3. Context-sensitive ethical and territorial data governance

P6 addresses context-sensitive ethical and territorial data governance because portability has a direct consequence: as it becomes easier to record location, photographs, and observations outside institutional spaces, the need to distinguish technical capability from legitimate data collection increases. On private property, within protected areas, communities, and Indigenous territories, data may be subject to consent, territorial sensitivity, sharing restrictions, and collective forms of authority. CARE provides specific principles for Indigenous data governance, while geoethics broadens the discussion of responsibility in geoscience practice (Carroll et al., 2020; Peppoloni & Di Capua, 2016).

P6 turns this issue into a design requirement proportional to context: a mature PGLI implementation should make visible who controls a record, where it remains, how it is exported, and when it should not be collected. In ITA ARANDU, local storage and user-initiated export reduce automatic extraction but do not yet constitute a complete governance solution. Granular controls for consent or territorial sensitivity are not present across all workflows. P6 therefore received a partial diagnosis. This gap is deliberately retained as a diagnostic finding and development agenda rather than concealed by the case narrative.

6.4. Portability in rural settings and contexts with variable infrastructure

The context of Mato Grosso do Sul makes one practical reason for portable infrastructure especially visible: the university and the geological features under study may be separated by great distances. The same logic may arise on farms and other rural properties, in rural schools, along roads, in remote areas, or in other environments where connectivity and access to equipment vary. The framework does not treat these settings as inherently deficient or presume a socioeconomic profile. It asks whether the learning infrastructure remains functional as the learner moves and what institutional supports are needed when a personal device is insufficient.

6.5. Epistemic transparency as infrastructure

One implication of the framework is to treat epistemic transparency as part of the infrastructure rather than as additional help text. If a map appears without scale or provenance, if a sensor reading appears without acquisition conditions, or if the interface automatically copies a mapped unit into an observation field, the system silently shapes the student's reasoning. Infrastructure is not neutral because it determines which distinctions remain visible. Making source, scale, method, precision, and uncertainty explicit is therefore an educational design decision.

This interpretation connects technology with epistemic cognition. Students need more than knowing how to 'use the app'; they need to learn when a data point supports an inference, when a scale is inappropriate, and when the absence of documented evidence generates a new question rather than a negative result. Bateman et al. (2022) show that uncertainty can be taught explicitly. PGLI extends this concern to interface architecture itself: the environment should make it difficult to overlook that observation, measurement, and interpretation have different epistemic statuses.

7. Limitations, threats to validity, and research agenda

The first limitation is that this is a conceptual study. No student learning data are available, and the paper does not support claims about performance, autonomy, inclusion, agency, critical thinking, or transfer to professional instrumentation. Second, the primary application applies the framework to a system developed by the authors themselves, creating a risk of confirmation bias; the illustrative contrastive application reduces but does not eliminate this limitation because it relies on published documentation rather than independent inspection of the platforms. Third, the literature synthesis is thematic and purposive rather than systematic; other researchers may group traditions differently or prioritize different principles. Fourth, the categories 'strong,' 'partial,' and 'not evidenced' have not yet been assessed for inter-rater agreement. Fifth, the digital-access indicators contextualize mobile-first design but do not characterize the future UFMS cohort.

The sixth limitation is technological. Smartphones and browsers are heterogeneous; sensors may be absent or behave differently; local storage can be lost; and offline operation requires preparation. The seventh is economic: the paper does not present a cost-benefit analysis and does not equate reduced dependence on additional infrastructure with zero cost. The eighth is conceptual: the six principles were formulated as a coherent set, but they still need to be challenged by experts and additional cases to assess redundancy, gaps, and transferability. P6 in particular should be refined with participation from communities and governance specialists when applied to territorially sensitive contexts. Table 8 summarizes the principal threats to interpretive validity, current safeguards, and future evidence needs.

Threat	Why it matters	Current safeguard	Future evidence needed
Author-developer circularity	The same group develops and analyzes the system.	Framework derived before application; negative categories allowed; illustrative contrastive application included.	External validation, inter-rater agreement, and application by other groups.
Function = learning	A resource can exist without producing competence or agency.	Language restricted to opportunity, design-level authorship, and correspondence.	Studies using tasks, rubrics, and observation of use.
Portability = inclusion	A mobile device is not universal and does not eliminate barriers.	Reduced additional dependencies rather than guaranteed access.	Access profiles and institutional loan/alternative strategies.

Threat	Why it matters	Current safeguard	Future evidence needed
Sensor = professional instrument	Conflates demonstration or training with metrology.	Explicit progression to professional instrumentation and failure conditions.	Hardware-specific tests and comparison with professional instruments.
Capacity to collect = legitimacy	Portability can expand data collection in sensitive territories without adequate governance.	P6 makes consent, control, sensitivity, and export explicit objects of inspection.	Co-design of protocols and governance validation with communities/managers.
Framework = universal	The principles may reflect the case and the selected literature.	Bounded domain of applicability; contrastive application; failure conditions.	Independent use in other courses, countries, and digital architectures.

Table 8. Threats to interpretive validity. The framework is presented as a testable and revisable theoretical proposition, not as a validated model.

The research agenda should proceed through complementary and sequenced lines of work. First, conceptual and content validation with external experts in geoscience education, field geology, educational technology, and data governance should assess the clarity, redundancy, sufficiency, and applicability of the six principles. At that stage, two or more independent raters should apply the Table 2 rubric to the same systems to test category consistency and estimate agreement using a statistic appropriate to the number of raters and the nature of the classification. Second, studies with students should examine record authorship, observation quality, use of scale, argumentation, treatment of uncertainty, and possible agency while comparing traditional, mobile, and combined workflows. Third, implementation studies should test devices, connectivity, local persistence, accessibility, additional costs, and transition to professional instrumentation. Keeping these lines distinct makes it possible to separate framework validity, infrastructure functioning, and educational effect.

8. Conclusions

This paper proposes Portable Geoscience Learning Infrastructure (PGLI) as a design and inspection framework for situations in which digital resources accompany students between university and field settings. The formulation does not define a minimum set of resources and does not predict learning. It organizes six inspectable design principles - portability and reduced dependence on additional infrastructure, continuity across settings, learner authorship of field records, epistemic transparency, progression to professional instrumentation, and context-sensitive ethical and territorial data governance - each associated with a failure condition and a procedure for detection at the design level.

The illustrative application to ITA ARANDU MS shows how the rubric can produce both strong and partial diagnoses within the same system, while the illustrative contrastive application to FieldMove, Svalbox/AG222, and Sedimentary Rock! yields distinct analytical profiles without serving as a quality ranking or external validation. This contrast matters because it indicates that PGLI is neither synonymous with mobile learning nor an exclusive description of ITA ARANDU; it is an operational vocabulary for asking what form of portable learning infrastructure a system provides, what it preserves, and where it fails or moves beyond its domain of applicability.

The contribution remains deliberately bounded. PGLI provides a starting point for designing, analyzing, and critiquing portable geoscience learning infrastructures; it does not demonstrate that smartphone use improves learning, autonomy, or equity. Its intended transferability does not depend on replicating ITA ARANDU MS, but on enabling other educators to apply the rubric, identify failures, and adapt the principles to different territorial, institutional, technological, and governance realities while preserving distinctions among evidence, interpretation, and professional validation. Including context-sensitive ethical and territorial data governance makes explicit that technical portability does not amount to unrestricted authorization to collect, geolocate, or share data. The framework's next test must be external: other educators need to be able to apply it using comparable criteria, identify failures, and propose revisions. Subsequent empirical studies should then examine whether particular configurations of portability are associated with observable changes in geoscience learning.

Software and materials availability

Public implementation: https://cbuson.github.io/atlas-geocientifico-ms/

Repository: https://github.com/cbuson/atlas-geocientifico-ms

Persistent record: https://doi.org/10.5281/zenodo.21923101

Version used for the illustrative application: V38.4.59-FIELD-ROBUSTNESS-20260910. The source code is publicly accessible under the PolyForm Noncommercial 1.0.0 license; the manuscript therefore uses 'source-available' rather than 'open source' in the strict sense.

Data availability statement

No new empirical participant data were generated or analyzed in this conceptual framework study. The software implementation and materials used for the illustrative application are publicly available through the ITA ARANDU MS deployment, GitHub repository, and Zenodo record listed above. The illustrative contrastive analysis relies on the published sources cited in the manuscript.

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Author contributions

Carlos Busón Buesa: Conceptualization, Methodology, Software, Investigation, Data curation, Visualization, Writing – original draft, Writing – review & editing. Sandra Garcia Gabas: Conceptualization, Validation, Investigation, Writing – review & editing. Both authors approved the final manuscript.

Declarations

Competing interests. The authors have no relevant financial interests to disclose. Both authors participate in the development and scientific curation of ITA ARANDU MS; this non-financial relationship is disclosed because it is directly relevant to the illustrative application presented here.

Ethics statement. This theoretical-conceptual study did not involve human participants or animals. Future studies involving students will require the applicable ethical approvals.

Use of generative AI. OpenAI ChatGPT (GPT-5.6 Sol) was used during manuscript preparation for language editing and consistency checking. The authors reviewed and verified the final content and take full responsibility for the manuscript.

Carlos Busón Buesa and Sandra Gabas takes responsibility for checking the accuracy of the English translation. The authors verified the originality and accuracy of the final content, including the references and all factual and numerical claims, and take full responsibility for the integrity of the manuscript.

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