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Review Article

Geoethics in forensic geoscience: Towards process ethics and forensic ethical literacy

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ABSTRACT: This paper advances an expanded conception of geoethics in forensic geoscience by extending ethical responsibility beyond the conduct of individual practitioners to encompass the broader processes through which forensic evidence is generated, interpreted, communicated, evaluated, and applied. We introduce Process Ethics as a complementary perspective that recognises ethical and epistemic responsibility as distributed across the interconnected actors, decisions, relationships, and institutions that shape the forensic investigative ecosystem. To translate shared geoethical principles into practice, we propose Relational Geoscientific Pragmatism (RGP) as a methodological approach integrating geoscience, relational thinking, and pragmatism to support context-sensitive and ethically defensible decision-making. We further discuss Forensic Ethical Literacy as a cross-cutting capability encompassing ethical awareness, critical judgement, reflexivity, scientific understanding, and responsible action throughout the investigative process. Education and professional development are identified as important mechanisms for fostering Forensic Ethical Literacy, with broader applications in professional practice, governance, and organisational decision-making. Building on these concepts, we propose the Adaptive Geoethical Investigation Framework (AGIF) as a three-layer conceptual framework linking Geoethical Foundations, RGP Methodology, and Forensic Implementation through iterative consideration of context, ethical and epistemic issues, actors and competencies, decisions and actions, and evaluation and reflection. AGIF is designed to accommodate diverse geological, environmental, cultural, institutional, and legal contexts while remaining grounded in shared geoethical commitments.. This proposed framework provides a conceptual architecture for embedding Process Ethics across forensic geoscience and the wider investigative ecosystem, supporting scientifically rigorous, ethically accountable, and context-responsive forensic practice.

KEYWORDS: ethics; forensic ethical literacy; forensics; geoforensics; geoethics; geology; soil

1 Introduction

Forensic Geoscience has become an increasingly important component of forensic science, supporting criminal and civil investigations through the application of geoscientific knowledge to the search, recovery, analysis, and interpretation of geological evidence. Its scope has expanded beyond conventional criminal investigations to include environmental crime, illicit exploitation and trafficking of natural resources, humanitarian investigations, and other contexts in which geological materials, processes, and landscapes intersect with human activities and legal questions. As the discipline has matured, significant efforts have focused on improving analytical methods, developing standardised protocols, and establishing professional standards that enhance the reliability, reproducibility, and credibility of forensic geological evidence.

Geoethics has similarly evolved [1, 2]. Initially concerned primarily with professional conduct in the geosciences [3, 4, 5, 6, 7, 8], it has now developed into a broader field concerned with the ethical principles and values that should guide human activities wherever geoscientific knowledge interacts with society and the Earth system [9, 10]. This evolution has shifted attention from compliance with professional standards towards ethical awareness, responsibility, reflexivity, and context-sensitive decision-making [11]. Within this perspective, scientific competence itself acquires an ethical dimension. Geoscientists are responsible not only for the technical quality of their work, but also for recognising uncertainty, communicating limitations transparently, considering the consequences of their decisions, and engaging responsibly with the individuals, institutions, communities, and environments affected by geoscientific practice [1,2,12].

Forensic geoscience provides a particularly important

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setting in which to explore this development. Unlike many other areas of geoscientific practice, forensic evidence is generated specifically to inform investigative and judicial decision-making [13–15]. Geological observations, sampling, interpretation and evaluation, and expert opinions may influence decisions affecting individual liberty, human rights, public safety, environmental protection, and the administration of justice. Consequently, ethical responsibility cannot be confined to the actions of the individual forensic geoscientist. It emerges throughout the entire processes by which evidence is recognised, recovered, analysed, interpreted, communicated, evaluated, and ultimately used. An important milestone in this development was A Proposal for a White Paper on Geoethics in Forensic Geology [16], which established a comprehensive ethical foundation for the discipline. The White Paper focused primarily on the responsibilities of the forensic geologist and articulated core values including competence, integrity, impartiality, transparency, responsibility, and effective communication. It further emphasised the importance of ethical conduct throughout forensic geological practice, from crime scene investigation and laboratory analysis to expert testimony, thereby providing a common ethical reference point for practitioners and the justice system.

Since the publication of the White Paper, however, the operational environment of forensic investigations has changed substantially. Rapid developments in artificial intelligence, machine learning [17,18], remote sensing, unmanned aerial systems, geographic information systems (GIS), and other digital technologies are transforming how forensic evidence is identified, collected, analysed, and interpreted. At the same time, investigators increasingly face complex and interconnected forms of criminality, including environmental crime, organised transnational crime, terrorism, international illicit trafficking of natural resources and cultural heritage, illegal waste disposal, and challenges associated with environmental and climate change [19–21]. These developments have intensified international collaboration and created a need for forensic practice that can operate effectively across diverse legal, institutional, environmental, and cultural contexts.

Alongside these technological and societal changes, a more fundamental shift has occurred in the structure of forensic investigations themselves. Contemporary investigations are conducted through multidisciplinary and highly interconnected systems involving crime scene investigators, law enforcement personnel, forensic scientists, intelligence analysts, prosecutors, judges, and an expanding range of technical specialists. Within such systems, the evidential significance of scientific observations is shaped progressively through multiple stages of decision-making. Evidence is collected, selected, analysed, interpreted, communicated, challenged, and evaluated by different actors, each contributing to the eventual outcome of the investigation and judicial process. The integrity and reliability of forensic evidence therefore depend not only on the competence and conduct of individual experts but also on the quality of the interactions, decisions, and relationships that connect the wider investigative ecosystem [22,23].

This evolution suggests a corresponding evolution in geoethics. While the ethical responsibilities of forensic geoscientists remain fundamental, they are no longer sufficient on their own to account for how forensic evidence acquires meaning and influence within modern investigative systems. Ethical responsibility must also be understood as a collective and process-oriented phenomenon. Decisions concerning scene management, sampling strategies, analytical approaches, interpretation of results, communication among stakeholders, and judicial evaluation all shape the evidential value of forensic information and its contribution to justice. Responsibility therefore extends beyond the individual practitioner to encompass the broader investigative and institutional processes through which forensic evidence is produced and used.

This paper presents a conceptual review of geoethical perspectives relevant to forensic geoscience. Rather than aiming to provide a systematic or exhaustive synthesis of the literature, the review brings together relevant conceptual and scholarly contributions from geoethics, forensic geoscience, professional and process ethics, forensic practice, ethical education, and emerging technologies. These sources are examined interpretatively to identify conceptual connections, gaps, and opportunities for extending geoethical thinking from individual professional conduct towards the broader processes and relationships that shape forensic investigations. This approach provides the conceptual basis for the perspective and framework developed in this paper.

The purpose of this paper is therefore not to revise the geoethical principles established in the White Paper [16], but to extend their application beyond the conduct of the individual practitioner to the wider investigative process. We propose process ethics as a complementary geoethical perspective in which ethical and epistemic responsibility is distributed across the actors, decisions, relationships, and institutional structures that shape forensic investigations. To support this perspective, we examine Relational Geoscientific Pragmatism (RGP) in geoethics as a methodological approach for translating shared geoethical principles into context-sensitive forensic decision-making [11]. We further introduce forensic ethical literacy as a cross-cutting capacity that enables participants throughout the investigative ecosystem to recognise and navigate ethical and epistemic challenges. In practice, this capacity could be assessed through brief scenario-based exercises, structured peer-review debriefs, or reflective case logs documenting how ethical and epistemic issues were identified and addressed. Finally, we propose the Adaptive Geoethical Investigation Framework (AGIF) as a forensic specific architecture for integrating geoethical principles, methodological reasoning, and practical decision-making. Together, these concepts provide a framework for embedding process ethics throughout forensic geoscience and the wider investigative ecosystem while supporting forensic practice that is scientifically rigorous, epistemically responsible, ethically defensible, and sensitive to context.

The four framework components introduced in this paper are closely interconnected but serve distinct functions within the proposed conceptual architecture. Process ethics provides the overarching ethical perspective; RGP provides the methodological approach through which geoethical principles can inform context-sensitive deliberation and action; Forensic

Ethical Literacy represents the cross-cutting capability required by the actors involved in the investigative ecosystem; and AGIF provides the forensic-specific architecture through which all these elements are integrated and operationalised. Their respective roles and relationships are summarised in Table 1.

2 From professional ethics to process ethics: Towards the ethics of the investigation process

The White Paper established the first comprehensive ethical framework specifically developed for forensic geoscience [16]. It identified the ethical principles that should guide the professional conduct of forensic geologists, emphasising scientific competence, integrity, impartiality, transparency, responsibility, effective communication, and respect for both scientific evidence and the justice system. The White Paper also highlighted the importance of maintaining rigorous professional standards throughout every phase of forensic geological practice, from crime scene activities to laboratory analyses and through to courtroom testimony. In doing so, it positioned geoethics as an essential component of professional excellence, strengthening both the credibility of forensic geoscience and public confidence in scientific evidence.

These principles remain fully valid and continue to constitute the ethical foundation of forensic geological practice. However, the context in which forensic investigations are conducted is in continual evolution. Investigations have become increasingly multidisciplinary, technologically advanced, and institutionally interconnected. Scientific evidence can no longer be interpreted by a single expert working in relative isolation, but through the interaction of multiple professionals working within a complex investigative and evidential ecosystem.

This evolution requires the establishment of a broader ethical perspective. While the White Paper primarily addressed professional ethics, that is, the ethical responsibilities of the forensic geologist as an individual scientific expert, the present paper argues that contemporary forensic investigations require the development of a complementary framework of process ethics, in which ethical responsibility is distributed across the entire investigative ecosystem. In this perspective, the ethical quality of an investigation depends not only on the integrity and competence of individual professionals, but also on the ethical soundness of the decisions, interactions, and institutional practices that collectively shape the investigative and evidential processes.

We define process ethics in forensic geoscience as a continuous, relational, and reflexive form of ethical responsibility embedded throughout the processes by which geoscientific evidence is recognised, generated, preserved, analysed, interpreted, communicated, evaluated, and used. Process ethics does not replace professional ethics; rather, it extends it by recognising that the ethical robustness of forensic evidence depends on interconnected decisions made by multiple actors across the investigative and judicial ecosystem.

The reliability of forensic evidence is determined not only by the competence and integrity of the forensic geologist but also by the quality and integrity of decisions made before, during, and after scientific examination. Crime scene detection and preservation, evidence recognition and recovery, sampling strategies, maintenance of the chain of custody, communication among investigators and experts, interpretation and evaluation of scientific findings, and the balanced and impartial assessment of evidence within judicial proceedings all contribute to the integrity of the investigative process. Errors, misunderstandings, cognitive biases, communication failures, procedural deficiencies, or ethically inappropriate decisions at any stage may compromise the quality and evidential value of forensic evidence, regardless of the technical excellence of the forensic analyses themselves.

Consequently, ethical responsibility should not be viewed solely as the domain of the forensic scientist. Rather, it should be understood as a collective responsibility shared across the entire investigative and evaluative process. Every actor involved in the generation, management, interpretation, communication, and application of forensic evidence contributes to the ethical quality and integrity of an investigation. In this broader perspective, geoethics in forensic geoscience evolves from a framework primarily governing individual professional conduct into a more comprehensive approach that supports scientific integrity, collaborative decision-making, institutional accountability, and responsible governance throughout the investigative process. This conceptual shift reflects a wider transformation occurring across the forensic sciences. Contemporary investigations increasingly depend on multidisciplinary teams in which forensic scientists, law enforcement officers, crime scene investigators, prosecutors, judges, intelligence analysts,

Table 1 Conceptual relationships and functional roles of the principal components of the proposed framework in forensic geoscience

Framework component	Primary purpose	Level of application	Relationship to the other components
Process ethics	Extends ethical responsibility from individual conduct to the processes and relationships shaping forensic investigations.	Overarching ethical perspective	Provides the ethical orientation for RGP, Forensic Ethical Literacy, and AGIF
Relational Geoscientific Pragmatism (RGP)	Guides context-sensitive and ethically defensible reasoning and decision-making.	Methodological approach	Translates process ethics into methodological reasoning and forms the methodological basis of AGIF
Forensic ethical literacy	Develops the awareness, judgement, reflexivity, and responsible action needed to address ethical and epistemic issues.	Cross-cutting capability	Enables actors to apply process ethics and engage with RGP and AGIF across the investigative process
Adaptive Geoethical Investigation Framework (AGIF)	Integrates geoethical principles, methodological reasoning, and implementation in forensic practice.	Conceptual and practical architecture	Integrates process ethics, RGP, and forensic ethical literacy into an adaptive framework for forensic investigation

environmental agencies, and policy makers operate as interconnected components of a single investigative ecosystem. Within such a system, ethical practice cannot rely solely on the integrity of individual practitioners. Instead, it emerges from the collective application of shared principles, an understanding of the capabilities and limitations of all the different types of evidence, in particular, scientific, effective and fair communication, transparency, accountability, and collaborative decision-making.

Ethical responsibility is therefore both distributed and cumulative: distributed because different actors exercise different forms of responsibility, and cumulative because decisions made at one stage constrain the epistemic and ethical possibilities available at subsequent stages.

Distributed responsibility should not, however, be understood as diluted accountability. Process ethics complements rather than replaces individual and institutional accountability by recognising that different actors may contribute to the same investigative process while retaining distinct responsibilities for their decisions and actions. Specific decisions should therefore remain attributable to identifiable individuals or institutions and be appropriately documented, with clarity regarding decision ownership, consultation, professional boundaries, and the justification of significant investigative choices. In this sense, process ethics strengthens rather than weakens accountability by making the distribution of responsibilities, the basis for decisions, and the relationships among those involved more explicit and traceable.

Accordingly, this paper proposes extending the geoethical framework introduced in the White Paper from a focus on the ethical responsibilities of individual forensic experts, in particular forensic geologists, to a broader consideration of the ethics of the investigative and evaluative processes. Rather than replacing established principles of professional ethics, we argue that these principles should be integrated within a framework of process ethics that encompasses the entire investigative ecosystem. Under this approach, geoethics becomes not only a guide for professional conduct but also a governance framework that supports scientific integrity, fosters interdisciplinary collaboration, strengthens institutional accountability, and promotes ethically informed decision-making throughout every stage of forensic investigations.

3 Relational geoscientific pragmatism (RGP) as a methodology for forensic process ethics

The transition from professional ethics to process ethics requires a methodology capable of connecting general ethical principles with the practical realities of forensic investigation. Relational Geoscientific Pragmatism (RGP) provides such a methodology. Developed within geoethics, RGP is an action-oriented and context-sensitive framework structured around three interconnected dimensions: Geoscience, Relationality, and Pragmatism [11].

The RGP approach is particularly important because ethical challenges in forensic investigations often arise not from deliberate misconduct but from ordinary decisions made under conditions of incomplete information, uncertainty, time pressure, institutional expectations, or competing legitimate objectives. RGP makes these decision points visible as sites of ethical responsibility [22]. It therefore shifts attention from ethics understood primarily as compliance with professional obligations towards ethics as an ongoing practice of critical reflection, deliberation, justification, and responsible action.

RGP also provides a framework through which established levels of geoethical responsibility, individual, interpersonal, societal, and environmental [1,8,24] can be considered within concrete forensic situations [16]. Individual competence, integrity, impartiality, epistemic humility, and awareness of bias operate within relationships among professionals and institutions [25–27]; these relationships influence outcomes that may affect justice, human rights, fairness, and public trust; and investigative decisions may simultaneously have consequences for environments, sites, soils, landscapes, and geological materials. The different levels of geoethical responsibility are therefore not independent layers but interconnected dimensions that may (and we argue should) converge within a single investigative decision.

This convergence is central to the concept of forensic process ethics proposed here. RGP provides the methodology through which ethical responsibility can be examined across the sequence of decisions by which forensic evidence is recognised, recovered, analysed, interpreted, communicated, evaluated, and used. It does not replace professional codes, scientific standards, legal safeguards, or established principles of forensic practice. Rather, it complements them by providing a framework for examining how such principles and standards should inform action when multiple actors, uncertainties, relationships, and consequences intersect in real investigative contexts.

From this perspective, the unit of ethical attention expands from the individual forensic geoscientist to the network of decisions and relationships through which forensic knowledge is produced and used. The resulting investigative ecosystem is therefore not conceived as a new ethical domain, but as the forensic expression of a relational and multi-level understanding of geoethical responsibility. RGP provides the methodological basis for analysing this ecosystem: geoscience establishes the epistemic conditions for responsible decision-making; relationality identifies the network of responsibilities and consequences within which those decisions occur; and pragmatism provides the deliberative process through which shared principles can be translated into context-sensitive and ethically defensible action.

The following Section develops this perspective by examining how ethical responsibility is distributed across the investigative ecosystem and how the decisions of different actors collectively influence the integrity, reliability, and fairness of forensic investigations.

3.1 Geoscience: scientific reliability and epistemic responsibility

The geoscience dimension concerns the scientific and epistemic foundations of forensic decision-making. In forensic geoscience, this includes the design of sampling strategies, the reliability and representativeness of data, the selection and validation of analytical methods, the interpretation and evaluation of geological evidence, the recognition and communication of uncertainty, and the competence required to undertake these activities responsibly.

Scientific competence is not merely a technical requirement but an ethical responsibility. Decisions concerning sampling, analytical methods, interpretation, and the expression of conclusions may influence investigative directions and judicial outcomes. Geoethical practice therefore requires practitioners to recognise the limits of both their methods and expertise, distinguish clearly between observations and interpretations, communicate uncertainty transparently, and avoid presenting conclusions with greater certainty than the evidence supports.

This dimension also requires attention to the conditions under which geoscientific knowledge is produced. Geological materials are inherently heterogeneous and shaped by complex environmental and anthropogenic processes. Responsible interpretation therefore demands sensitivity to scale, context, representativeness, and alternative explanations. Within RGP, epistemic humility, the recognition that scientific knowledge is provisional, uncertain, and open to revision, is a central ethical obligation.

3.2 Relationality: Forensic evidence within networks of responsibility

The relational dimension recognises that forensic knowledge is produced, interpreted, and applied within networks of relationships rather than by individuals acting in isolation. Forensic investigations bring together forensic geoscientists, crime scene personnel, investigators, laboratories, legal professionals, policy makers, institutions, affected individuals, the court, and, in some cases, the environments and locations that constitute the subject of investigation.

These relationships influence both the production of evidence and the meaning attributed to it. Investigators depend on scientific expertise to understand evidential significance, while scientists depend on investigators for context, information, and access. Legal professionals rely on experts to communicate complex findings accurately and impartially and in an easily understood way. Decisions made by one actor inevitably influence the decisions available to others. Consequently, ethical attention extends beyond individual conduct to encompass the quality of interactions through which evidence moves across the investigative process. Communication, transparency, trust, independence, respect for professional boundaries, and recognition of different forms of expertise become integral elements of forensic process ethics. Relationality also requires awareness of institutional pressures and power asymmetries that may influence how evidence is generated, interpreted, communicated, or used.

Importantly, the relational dimension expands the scope of ethical responsibility beyond professional actors alone. Forensic decisions may affect victims, suspects, families, communities, institutions, and society. In investigations involving environmental crime, resource exploitation, or landscape disturbance, they may also affect soils, ecosystems, geological sites, and wider environmental systems. Ethical reasoning must therefore account for the broader network of human and environmental relationships within which forensic practice operates.

3.3 Pragmatism: Ethical deliberation in context

The pragmatic dimension provides the deliberative mechanism through which ethical principles are translated into action. Although principles such as integrity, impartiality, transparency, responsibility, justice, respect for persons, and scientific reliability remain fundamental [1,28], they do not by themselves determine the correct course of action in every forensic situation.

Pragmatism therefore emphasises the need to consider how these principles should be applied in specific circumstances, taking into account available evidence, uncertainty, alternative courses of action, operational constraints, institutional expectations, and potential consequences. It does not imply that ethical decisions should be based on expediency. Rather, it supports context-sensitive and proportionate action while maintaining consistency with foundational geoethical commitments.

In forensic investigations, pragmatic deliberation is particularly relevant when different legitimate objectives must be balanced, or when decisions must be made despite incomplete information and uncertainty. It encourages practitioners and other actors to make the reasoning behind significant decisions explicit, to consider possible consequences, and to remain open to revising decisions as new evidence or information becomes available.

3.4 Integrating the three dimensions of RGP: From principles to process ethics

The strength of RGP lies not in the independent application of its three dimensions but in their integration. Ethical decision-making in forensic geoscience requires simultaneous consideration of the reliability of scientific knowledge, the network of relationships through which that knowledge is produced and applied, and the practical consequences of alternative courses of action. A decision can therefore be regarded as fully responsible only when it is scientifically robust, relationally aware, and pragmatically justified.

Taken together, the three dimensions encourage reflection on three interrelated questions: What does the available geoscientific evidence allow us to know, and with what degree of uncertainty Who and what are affected by, involved in, or responsible for this decision What course of action is most ethically defensible in the circumstances, given the available evidence, uncertainties, alternatives, and potential consequences

These questions are not intended as a prescriptive checklist. Rather, they provide a repeatable deliberative structure through which ethical reasoning can accompany scientific and investigative decision-making.

This integration is central to the concept of forensic process ethics proposed in this paper. RGP provides the methodological basis for examining ethical responsibility across the sequence of decisions through which forensic evidence is recognised, recovered, analysed, interpreted, communicated, evaluated, and used. It does not replace professional standards, legal safeguards, or existing codes of practice. Rather, it complements them by providing a framework through which ethical principles can be translated into context-sensitive and defensible action.

From this perspective, the focus of ethical analysis expands from the conduct of the individual forensic geoscientist to the broader network of decisions and relationships through which forensic knowledge is produced and applied. Geoscience

provides the epistemic foundation for responsible decision-making; relationality identifies the network of responsibilities and consequences within which decisions occur; and pragmatism provides the deliberative process through which shared principles are translated into action. Together, they constitute the methodological foundation of a process-oriented geoethics for forensic geoscience.

4 Ethics across the investigative ecosystem

The shift from professional ethics to process ethics broadens ethical responsibility beyond the forensic geologist or forensic scientist. When forensic investigations are viewed as collaborative and multidisciplinary processes, ethical accountability cannot be assigned solely to scientific experts. Instead, it becomes a shared obligation among all those whose decisions influence the generation, management, interpretation, communication, and use of forensic evidence [1,8,16].

Ethical decisions arise throughout the whole investigative process. Crime scene managers must secure and preserve scenes to prevent contamination, protect evidence, minimise loss, and facilitate safe and effective recovery. Investigators are responsible for developing and testing hypotheses while actively reducing the influence of cognitive and confirmation bias [22,23]. Law enforcement officers must ensure that evidence is collected lawfully and that the chain of custody is maintained. Forensic scientists have a duty to communicate the strengths, limitations, and uncertainties of their approach and findings objectively and transparently, while considering competing propositions and alternative explanations [29,30]. Prosecutors and judges must critically evaluate scientific evidence, recognising both its probative value and also its limitations. Policymakers and institutional leaders also play an important role by shaping organisational culture, allocating resources, and establishing procedures that support good ethical practice.

Although these responsibilities differ according to the professional role, they are closely interconnected. Every participant contributes to a sequence of decisions that affects the quality, reliability and admissibility of forensic evidence. Ethical failures at any stage may undermine an investigation, regardless of the quality of the scientific analyses performed. Conversely, sound decisions at one stage often depend on the quality of decisions made earlier in the process. Scientific integrity therefore emerges not simply from the conduct of individual professionals, but from the cumulative effect of ethically informed decisions made throughout the investigative process.

This systems-based understanding of ethical responsibility is consistent with the broader framework of geoethics, which recognises responsibilities operating at individual, interpersonal, societal, and environmental levels [1,8,24]. Applied to forensic geoscience, these levels provide a useful framework for understanding the multiple and interconnected dimensions of responsibility within the investigative ecosystem [16].

At the individual level, geoethical responsibility includes integrity, competence, impartiality, epistemic humility, and awareness of potential personal bias in the production and evaluation of geoscientific evidence. At the interpersonal and professional level, it concerns communication, collaboration, and the fair and safe allocation of responsibilities among forensic scientists, investigators, law enforcement personnel, legal professionals, courts, institutions, and other stakeholders. At the societal level, forensic practice raises issues of justice, human rights, fairness, public trust, and the wider consequences of investigative and judicial decisions for individuals and communities. The environmental level is particularly relevant to forensic geoscience because evidence recovery may disturb soils, sediments, landscapes, geological materials and search sites, while forensic geoscientists may also contribute directly to investigations of environmental crime and environmental harm.

These domains should not be viewed as separate categories of responsibility. In practice, they frequently overlap. A decision about sampling strategy for example, may simultaneously involve professional competence, communication with other investigators, implications for judicial fairness, and physical impacts on a site or geological material. The concept of the investigative ecosystem therefore does not introduce a new ethical framework. Rather, it extends established geoethical principles into the specific context of forensic investigation, making explicit how ethical responsibility operates simultaneously across multiple scales, from individual judgement to institutional practice and wider societal and environmental consequences.

From this perspective, what unites all actors within the investigative ecosystem is not their specific professional role but their participation in a continuous process of decision-making. Decisions concerning crime scene preservation, evidence recovery, sampling strategies, interpretation of findings, interdisciplinary communication, and judicial evaluation can all strengthen or weaken the integrity of an investigation. This highlights the value of a decision centred approach to ethics, in which ethical analysis focuses not only on the behaviour of individuals but also on the decisions and interactions that shape the investigative process as a whole. Such an approach does not replace professional ethics. It broadens and strengthens it by recognising that ethical accountability is embedded throughout the processes by which scientific evidence is generated, managed, interpreted, communicated, and ultimately used in the pursuit of justice.

Recognising ethics as a shared responsibility also has important implications for professional development. If all participants contribute to the ethical quality of forensic investigations through the decisions they make, ethical competence cannot be confined to specialised training for forensic scientists alone. Instead, ethical awareness, critical thinking, informed decision-making, and an understanding of the capabilities and limitations of scientific evidence should become essential elements of education and continuing professional development for all participants in the investigative process. This provides the foundation for a broader model of ethical education across the investigative and evaluative ecosystem, which is discussed in the following Section.

5 Ethical education across the investigative ecosystem

The recognition that ethical responsibility is distributed throughout the investigative ecosystem has important implications for education and professional development [31–33]. If ethics is understood as a property of the investigative process rather than solely of individual practitioners, then ethical training must extend beyond the traditional boundaries of forensic science. It should form an integral component of professional development for all those who contribute to the generation, management, interpretation, communication, and evaluation of forensic evidence, including investigators, law enforcement personnel, forensic scientists, prosecutors, judges, and institutional leaders. Such education should seek not only to promote adherence to ethical principles but also to develop the capacity for critical reflection, interdisciplinary collaboration, and ethically informed decision-making. Ethical competence thus becomes a shared professional attribute that strengthens the integrity, effectiveness, and legitimacy of forensic investigations.

The objective of this educational approach is not simply to transmit ethical principles but to cultivate what may be termed Forensic Ethical Literacy. Whereas traditional ethics training often emphasises compliance with professional codes and regulatory requirements, Forensic Ethical Literacy integrates ethical awareness with an understanding of scientific reasoning and investigative decision-making. It may be defined as the capacity to recognise the ethical and epistemic dimensions of forensic decisions [1,11,24]; to understand the capabilities, limitations, uncertainties, and potential consequences of scientific evidence; to identify relevant responsibilities, stakeholders, values, and potential conflicts; and to exercise and communicate context-sensitive ethical judgement throughout investigative and judicial processes [34–36]. In this sense, Forensic Ethical Literacy represents a foundational competence for all participants in the investigative ecosystem, enabling them to integrate scientific understanding, ethical responsibility, and operational decision-making in ways that support fair, transparent, and accountable investigations.

For law enforcement personnel, Forensic Ethical Literacy has particular practical significance because investigators are often the first decision-makers in the forensic process. The observations they make, the hypotheses they formulate, the priorities they give, the evidence they recognise, and the expertise they seek can profoundly influence the direction and quality of an investigation. Their ability to identify potentially significant geological and environmental evidence, appreciate its relevance, and engage appropriate scientific expertise at an early stage is therefore critical to maintaining the integrity of the investigative process. In this context, ethical decision-making extends beyond the correct collection, preservation, and prioritisation of evidence. It also includes informed judgement regarding when scientific methods should be applied, what their limitations may be, and how their results can contribute to a fair, objective, and evidence-based investigation.

A further essential dimension of Forensic Ethical Literacy is an appreciation of the strengths, limitations, and uncertainties inherent in forensic science. Investigators, prosecutors, judges, and institutional decision-makers must recognise that scientific evidence rarely provides definitive answers in isolation. Rather, it should be interpreted within a framework that acknowledges uncertainty, probabilistic reasoning, methodological constraints, and competing explanations. Awareness of these factors helps to mitigate unrealistic expectations of scientific evidence, reduce the risks of confirmation bias and overinterpretation, and promote the accurate communication and appropriate evaluation of forensic findings throughout both investigative and judicial processes.

Ethical education should therefore be interdisciplinary and, where possible, transdisciplinary, drawing upon the knowledge, perspectives, and experiences of the diverse actors who comprise the investigative ecosystem. It should also be practice-oriented and continuous. While initial professional education establishes the foundations of ethical awareness and professional conduct, the rapidly evolving nature of forensic science, investigative technologies, and contemporary crime demands ongoing learning throughout a professional career. Continuous professional development enables practitioners to adapt to emerging scientific methods, technological innovations, evolving legal frameworks, and new ethical challenges [31–33]. Ethical competence should consequently be understood as a dynamic capability that is developed through formal education, operational experience, interdisciplinary collaboration, reflective practice, and sustained engagement with scientific, legal, and societal change.

A comprehensive educational framework should also foster mutual understanding across the investigative ecosystem. Effective collaboration requires not only professional expertise but also a clear appreciation of the roles, responsibilities, capabilities, and constraints of other participants in the investigative process. Investigators should understand the scientific principles underlying forensic evidence, while forensic scientists should appreciate the operational, legal, and practical realities within which investigations are conducted. Prosecutors and judges require sufficient scientific literacy to evaluate expert evidence critically and proportionately, while institutional leaders and policymakers should understand how governance structures, resource allocation, and professional training influence investigative quality and ethical practice. By fostering a shared culture of scientific understanding and collaboration, forensic institutions can strengthen communication, improve decision-making, enhance interdisciplinary cooperation, and promote public trust in both forensic science and the justice system.

Within this framework, the forensic geologist occupies a distinctive position as both a scientific specialist and a potential bridge between different components of the investigative ecosystem. Forensic geoscientists may contribute even before a crime scene is identified, supporting search strategies, environmental intelligence, and landscape assessments, and may remain involved through evidence recovery, laboratory examination, interpretation, and judicial proceedings. Their participation across multiple stages of the investigative process provides a unique perspective on how decisions made by different actors influence the quality and integrity of forensic evidence. Consequently, forensic geologists are particularly

well placed to contribute to the development of Forensic Ethical Literacy and to promote a culture of ethical, scientifically robust, and evidence-informed decision-making throughout the investigative ecosystem.

6 Contextualising universal principles: Different countries, ethical priorities and legal traditions

The ethical principles that underpin forensic geoscience, and forensic investigations more broadly, can be understood as shared normative foundations across diverse contexts. Integrity, impartiality, scientific competence, transparency, accountability, and respect for human rights should guide all participants in the investigative process, regardless of geographical location, legal jurisdiction, or cultural context. However, their interpretation, prioritisation, and practical balancing may vary across jurisdictions, cultures, and institutional settings. Collectively, these principles provide a common ethical foundation that supports scientific credibility, public confidence in forensic science, trust in investigative processes, and the fair administration of justice.

However, while ethical values may be shared, their practical implementation cannot be uniform. Forensic investigations take place within highly diverse environmental, geological, legal, institutional, and socio-cultural contexts [37]. Consequently, educational approaches and professional training cannot follow a single standardised model, but must instead be adapted to the specific characteristics and requirements of individual countries, jurisdictions, and investigative environments. The context in which forensic investigations occur influences both the nature of the crimes encountered and the ways in which forensic geoscience can contribute to investigative activities.

Geological settings influence the characteristics of soils, sediments, rocks, and landscapes that may become forensic evidence, while climatic and environmental conditions affect the preservation, transfer, and interpretation of geological traces [13–15,19–21,37]. Legal systems establish different procedural requirements governing the collection, admissibility, presentation, and evaluation of scientific evidence [38]. Institutional structures, law enforcement organisations, judicial procedures, and regulatory frameworks shape how forensic expertise is requested, communicated, and incorporated into investigations. Cultural and societal factors further influence public expectations of scientific evidence, levels of institutional trust, perceptions of professional responsibility, and relationships between scientific experts and judicial authorities. Investigative practices and policing cultures likewise vary according to national traditions, operational procedures, available resources, and accumulated professional experience.

These differences affect not only investigative strategies but also the ethical challenges encountered throughout the forensic process. Ethical education should therefore adopt a context-sensitive approach in which shared geoethical principles provide a common foundation, while educational programmes remain sufficiently flexible to address the geological, environmental, legal, organisational, cultural, criminological, and forensic characteristics of the jurisdictions in which professionals operate. Such adaptability does not weaken the role of shared ethical principles; rather, it enhances their practical relevance by ensuring that ethical competence remains closely connected to the realities of professional practice.

A further dimension of this contextual approach involves recognising when specific forms of scientific expertise are required. Rather than relying exclusively on standardised investigative models, practitioners should develop the ability to assess each case within its environmental, geological, legal, operational, and social context and to identify the most appropriate scientific methods and expertise to support the investigation. This capacity for contextual judgement represents a key component of Forensic Ethical Literacy, enabling professionals to make decisions that are scientifically justified, ethically informed, proportionate, and responsive to the circumstances of each case.

An important aspect of contextual adaptation concerns the diversity of legal systems within which forensic investigations operate. The role of scientific evidence, the responsibilities of experts, and the processes by which evidence is evaluated differ across legal systems that may be broadly characterised as adversarial, inquisitorial, mixed, religious, or customary [16, 39]. These categories are analytical rather than homogeneous, and substantial variation may exist within each category. Although shared geoethical principles provide a common ethical foundation, their practical application must be responsive to the legal framework in which an investigation is conducted.

In legal systems that may be broadly characterised as adversarial, such as those commonly found in the United Kingdom, United States, Canada and Australia, scientific evidence is typically presented by opposing parties and scrutinised through challenge and cross-examination. In these circumstances, geoethical responsibilities place particular emphasis on scientific independence, impartiality, transparency, effective communication, and the explicit acknowledgement of limitations and uncertainties. Forensic geoscientists must maintain neutrality, avoid overstating conclusions, and ensure that evidence is not selectively interpreted to support either party's position [39]. Their primary responsibility remains to the court and the pursuit of scientific truth.

In legal systems that may be broadly characterised as inquisitorial or mixed, often associated with many continental European jurisdictions, judicial authorities may play a more active role in directing investigations, evaluating evidence, and in some cases, directly appointing forensic experts [39]. Within these systems, geoethical responsibilities similarly emphasise scientific independence, methodological rigour, transparency, accountability, and effective communication between experts and judicial authorities. The principal ethical challenge is often not the contest between competing expert opinions but ensuring that scientific evidence is collected, interpreted, communicated, and incorporated into decision-making in a scientifically robust, objective, and transparent manner. In mixed systems, where adversarial and inquisitorial elements coexist, ethical safeguards must support both the independence of scientific expertise and the integrity of interactions among the various actors involved in the investigative and judicial

process.

Religious and customary legal traditions, which are themselves diverse, may introduce additional ethical considerations arising from cultural values, community expectations, religious beliefs, and differing conceptions of justice. Investigations may involve sensitivities relating to burial practices, human remains, sacred landscapes, land ownership, environmental stewardship, or community relationships. In such contexts, geoethical principles require investigators and forensic experts to balance legitimate scientific objectives with respect for cultural and religious values while maintaining scientific integrity and protecting fundamental human rights.

Despite substantial differences in legal structures and procedures, shared ethical principles remain relevant across diverse contexts. Integrity, competence, impartiality, transparency, accountability, respect for human dignity, and commitment to scientific truth retain their significance regardless of jurisdiction, although their interpretation and practical application may differ. Geoethics does not replace legal norms or procedural rules; rather, it provides a common ethical foundation capable of supporting responsible forensic practice across diverse legal, cultural, and institutional environments.

The challenge, therefore, is not to choose between shared ethical principles and contextual adaptation, but to integrate both within a coherent framework. Core ethical values can provide a stable common foundation, while their interpretation, prioritisation, and practical application may be adapted to the specific needs of different forensic environments. Geoethics should therefore be understood not as a fixed set of rules, but as a dynamic framework that combines enduring ethical principles with context-sensitive implementation. This balance between shared principles and adaptability forms the foundation of the Adaptive Geoethical Investigation Framework (AGIF) proposed in Section 8, providing a basis for forensic investigations that are scientifically rigorous, ethically robust, and operationally effective.

7 Emerging technologies and new geoethical challenges

The rapid development of emerging technologies is transforming forensic geoscience, the wider forensic sciences, and the investigative process itself. Advances in Artificial Intelligence (AI), machine learning, remote sensing, Unmanned Aerial Systems (UAS), Geographic Information Systems (GIS), environmental DNA (eDNA), geospatial modelling, robotics, digital mapping, and increasingly sophisticated analytical instrumentation are expanding the ability of investigators to detect, collect, analyse, and interpret evidence. These innovations offer significant opportunities to improve the efficiency, accuracy, and scope of forensic investigations. At the same time, they introduce new ethical challenges that extend beyond the traditional responsibilities of individual practitioners and affect the wider investigative ecosystem [40,41].

From a geoethical perspective, technology should be understood as a tool that supports, rather than replaces, scientific judgement and professional responsibility. The increasing use of automated and data-driven systems can create a perception that technological outputs are inherently objective or free from bias. In reality, all technologies operate within frameworks shaped by human decisions regarding data collection, algorithm design, analytical parameters, interpretation, validation, and reporting. Ethical responsibility therefore remains inseparable from the individuals and institutions that develop, implement, oversee, and apply these technologies.

Artificial Intelligence (AI) and Large Language Models (LLMs) present particularly important ethical considerations [17,18]. AI-assisted systems are increasingly capable of supporting crime scene detection, search planning, predictive modelling, image analysis, environmental monitoring [17,18,40–42] and the interpretation of complex geospatial datasets [43]. While these tools may enhance investigative efficiency and analytical capacity, they also raise concerns relating to transparency, explainability, accountability, bias, reproducibility, and effective communication. Investigators, forensic scientists, legal practitioners, and judges may increasingly be required to assess conclusions supported by algorithms whose decision-making processes are not always fully transparent. The ethical challenge is therefore not simply whether such technologies can be used, but how they can be used responsibly. Their implementation requires an appropriate balance between technological innovation and human oversight, ensuring that conclusions remain scientifically justified, explainable, transparent, and capable of independent scrutiny [17,18].

The growing integration of digital and geospatial technologies also raises important questions concerning data governance. Contemporary investigations increasingly rely on large datasets derived from satellite imagery, environmental monitoring systems, geographic databases, mobile devices, digital records, and other geospatial and environmental sources. The collection, storage, sharing, analysis, and long-term management of such data must be undertaken in a manner that respects legal requirements, privacy considerations, security obligations, and the principles of scientific integrity [40,41]. Ethical governance therefore requires robust procedures for validation, quality assurance, documentation, transparency, and accountability throughout the life cycle of digital evidence. This also includes attention to training-data provenance, validation for intended use, data security, version control, and audit trails, particularly where automated or proprietary systems are involved.

Emerging technologies also reinforce the importance of interdisciplinary and transdisciplinary collaboration. Effective deployment of advanced analytical tools frequently requires cooperation among geoscientists, digital specialists, data scientists, statisticians, law enforcement personnel, legal professionals, crime scene managers and policymakers [40,41]. Ethical challenges may arise not only from technological limitations but also from misunderstandings regarding their capabilities, assumptions and uncertainties. Consequently, clear communication across disciplinary boundaries becomes a critical component of both ethical practice and investigative effectiveness. The reliability of technological evidence depends as much upon the quality of collaboration and interpretation as upon the performance of the technology itself.

These developments further reinforce the importance of

Forensic Ethical Literacy. Participants throughout the investigative ecosystem should possess sufficient understanding to recognise the capabilities, limitations, uncertainties, and potential biases associated with technological tools and analytical methods. Ethical competence in contemporary forensic investigations therefore includes the ability to critically evaluate technological outputs, question sources of uncertainty, appreciate the evidential significance of digitally derived information, and avoid overreliance on automated systems. Forensic Ethical Literacy enables professionals to ensure that technological innovation remains aligned with the broader objectives of scientific integrity, transparency, accountability, and justice.

These technology-related considerations are also relevant to the conceptual framework proposed in this paper. Emerging technologies provide a useful example of how geoethical principles, scientific reasoning, professional responsibilities, and contextual factors must be considered together throughout the investigative process. Issues such as training-data provenance, validation for intended use, automation bias, human oversight, version control, audit trails, data security, and responsibility for proprietary systems may arise at different points in an investigation and involve multiple actors and levels of responsibility. These considerations illustrate the types of technological and ethical challenges that a structured, adaptive, and iterative approach to forensic investigation should be able to accommodate.

At a broader level, emerging technologies illustrate the importance of a process-based approach to ethics. The ethical implications of technology are rarely confined to a single individual or professional role. Decisions concerning data acquisition, algorithm development, model validation, interpretation, reporting, disclosure, and judicial evaluation are distributed across multiple actors and institutions. Ethical responsibility therefore extends throughout the investigative ecosystem, reflecting the interconnected nature of modern forensic practice.

Emerging technologies do not diminish the relevance of geoethics; rather, they make it increasingly important. As forensic investigations become more data-driven, digitally interconnected, and technologically sophisticated, the need for shared ethical principles and ethically informed decision-making becomes even more critical. Geoethics provides a framework through which technological innovation can be integrated responsibly into forensic investigations, ensuring that scientific advances contribute not only to investigative effectiveness but also to transparency, accountability, public trust, and the fair administration of justice.

8 Adaptive geoethical investigation framework (AGIF): Operationalising Relational Geoscientific Pragmatism (RGP) in forensic practice

The evolution from professional ethics to process ethics requires more than the articulation of ethical principles. It requires a practical mechanism for translating those principles into context-sensitive decisions and actions throughout the investigative process. Relational Geoscientific Pragmatism (RGP) provides this methodological foundation by integrating geoscientific knowledge, relational awareness, and pragmatic ethical reasoning in a manner that is responsive to uncertainty, stakeholder interactions, institutional settings, and the consequences of action [11].

Building upon this foundation, AGIF is proposed as a forensic-specific conceptual framework for operationalising RGP within forensic investigations. At this stage, AGIF represents a conceptual proposal rather than an empirically validated framework and therefore requires future empirical application, testing, and evaluation across different forensic contexts. Its intended applications span several levels: at the individual level, AGIF is intended to support ethically informed decision-making; at the educational and professional level, it can inform the development of Forensic Ethical Literacy and professional training; at the organisational level, it can support governance, procedural design, and institutional decision-making; and at the investigative-process level, it can provide a basis for evaluating and improving how ethical and epistemic considerations are integrated throughout forensic investigations.

AGIF is organised into three interconnected layers. The first establishes the geoethical principles, values, and levels of responsibility that provide a shared ethical foundation across jurisdictions, legal traditions, and professional roles. These principles serve as the normative basis for responsible forensic practice, irrespective of the specific context in which an investigation takes place.

The second layer incorporates the three dimensions of Relational Geoscientific Pragmatism: Geoscience, Relationality, and Pragmatism. Together, these dimensions provide the methodological bridge between universal geoethical commitments and the realities of forensic practice. They guide how ethical principles are interpreted and applied in relation to scientific evidence, stakeholder relationships, institutional structures, and the practical challenges of decision-making under conditions of uncertainty.

The third layer translates these ethical and methodological foundations into an adaptive process of forensic implementation. This process encompasses five interconnected components: Context, Ethical and Epistemic Issues, Actors and Competencies, Decisions and Actions, and Evaluation and Reflection. These components provide a structured means of identifying relevant circumstances, recognising ethical and epistemic challenges, understanding the responsibilities and capabilities of those involved, supporting informed decision-making, and promoting continuous learning and improvement.

Across all three layers, Forensic Ethical Literacy functions as a cross-cutting capability that links ethical awareness, scientific understanding, critical reflection, professional judgement, and responsible action.

AGIF should therefore not be regarded as an alternative to RGP. Rather, it represents a forensic specific architecture through which RGP can be translated into forensic practice. By linking universal geoethical principles to contextual understanding, interdisciplinary collaboration, and reflective decision-making, AGIF is intended to provide a basis for applying shared ethical commitments within diverse geological, environmental, legal, institutional, cultural, and operational settings (Fig. 1).

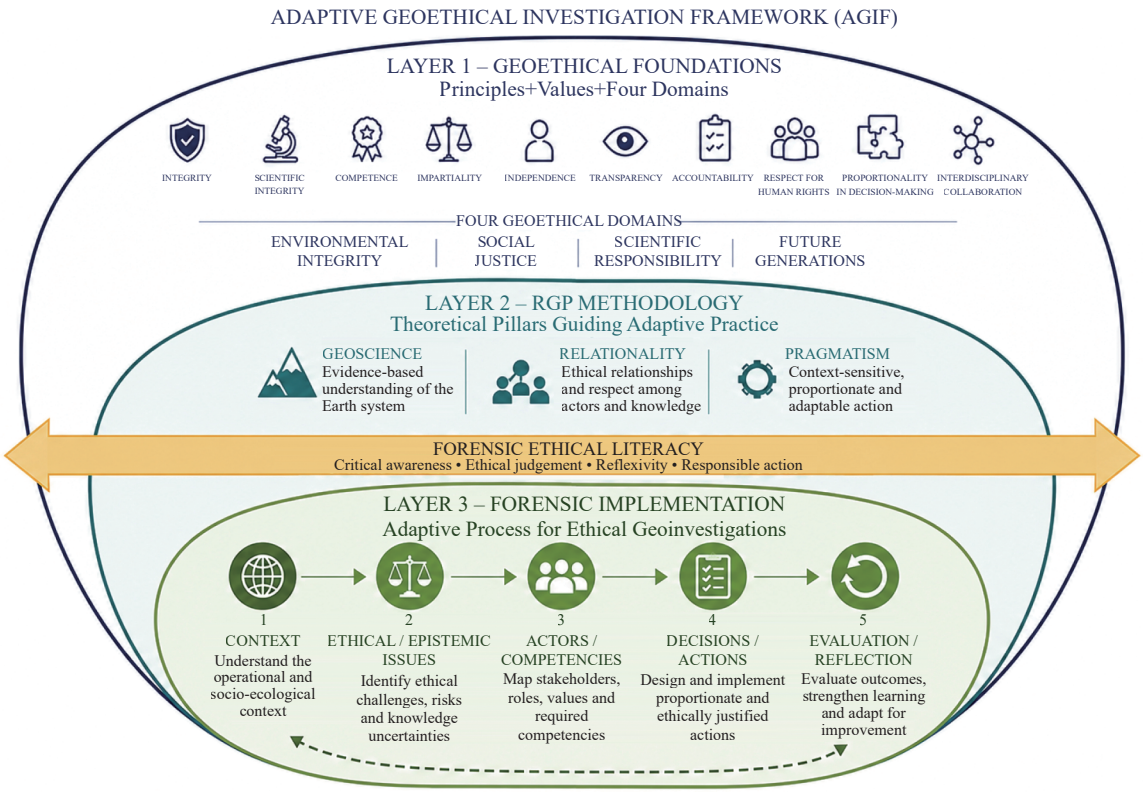


Figure 1 The Adaptive Geoethical Investigation Framework (AGIF): a three-layer conceptual framework integrating Geoethical Foundations, Relational Geoscientific Pragmatism (RGP) Methodology, and Forensic Implementation. Forensic Ethical Literacy operates across the three layers as a cross-cutting capacity linking critical awareness, ethical judgement, reflexivity, and responsible action throughout the investigative process. The framework is intended to be used iteratively: users move through the layers as an investigation progresses, while feedback from outcomes, emerging evidence, stakeholder interactions, and reflective assessment informs subsequent decisions and may prompt revision of earlier steps. Conceptual framework developed by the authors; graphical visualization generated with the assistance of ChatGPT (OpenAI) and subsequently refined by the authors to ensure fidelity to the conceptual model.

Figure 1 was developed from the conceptual model defined by the authors. Following AI-assisted graphical generation, the figure was reviewed and refined to ensure that its visual structure and relationship accurately reflected the proposed framework.

8.1 Layer 1. Geoethical foundations: Principles, values, and geoethical Domains

The first layer represents the normative and ethical foundation of AGIF (Fig. 1). It establishes the principles, values, and geoethical domains that should underpin forensic geoscience practice irrespective of geographical, legal, institutional, cultural, or political context. Rather than prescribing specific investigative procedures, this layer provides a common ethical reference against which professional conduct, scientific reasoning, and investigative decisions can be assessed.

The levels of responsibility discussed in earlier sections and the geoethical domains used in AGIF describe complementary dimensions of geoethical responsibility rather than equivalent classifications. The former identify where responsibility operates across the investigative ecosystem, whereas the latter identify what substantive ethical concerns are addressed. Accordingly, the four AGIF domains provide a thematic structure through which responsibilities operating at individual, interpersonal, societal, and environmental levels can be considered in forensic practice.

The core principles include: integrity; scientific integrity①; competence; impartiality; independence; transparency; accountability; respect for human rights and human dignity; proportionality in decision-making and interdisciplinary collaboration.

Integrity is used here in the broader ethical sense of consistency between principles, responsibilities, decisions, and conduct across the investigative process, whereas scientific integrity refers specifically to the responsible generation, analysis, interpretation, communication, and use of scientific knowledge and evidence. The distinction recognizes that an investigation may raise questions of integrity that extend beyond scientific practice itself, while scientific integrity concerns the epistemic and methodological reliability of the

① Integrity is used here in the broader ethical sense of consistency between principles, responsibilities, decisions, and conduct across the investigative process, whereas scientific integrity refers specifically to the responsible generation, analysis, interpretation, communication, and use of scientific knowledge and evidence. The distinction recognises that an investigation may raise questions of integrity that extend beyond scientific practice itself, while scientific integrity concerns the epistemic and methodological reliability of the processes through which scientific evidence is produced and evaluated.

processes through which scientific evidence is produced and evaluated.

These principles provide a shared ethical language for forensic geoscientists, investigators, judicial authorities, institutional decision-makers, and other actors involved in the investigative process. Although their interpretation and practical application may require contextual adaptation, their normative function remains consistent across investigative settings.

AGIF situates these principles within four interconnected substantive geoethical domains: environmental integrity, social justice, scientific responsibility, and responsibility toward future generations. These domains should be understood as complementary to the levels of responsibility identified earlier in the manuscript: they describe the principal areas of ethical concern through which responsibilities operating at individual, interpersonal, societal, and environmental levels can be considered. Layer 1 therefore defines both the ethical standards for professional action and the broader substantive domains within which such action takes place..

8.2 Layer 2. Relational geoscientific pragmatism (RGP) methodology: Theoretical pillars guiding adaptive practice

The second layer provides the methodological bridge between universal geoethical foundations and their application in specific forensic contexts (Fig. 1). It is structured around three complementary pillars: Geoscience, Relationality and Pragmatism (RGP), which guide the translation of ethical principles into context-sensitive investigative practice. Geoscience anchors the framework in an evidence-based understanding of Earth systems, geological processes, materials, spatial relationships, and environmental conditions. It emphasises that ethically responsible forensic practice must remain scientifically robust and attentive to the uncertainties, limitations, and interpretative boundaries of geoscientific evidence. Relationality recognises that forensic investigations do not occur in isolation but within networks of relationships among experts, investigators, judicial authorities, institutions, affected communities, environments, and different forms of knowledge.

Pragmatism provides the adaptive dimension of the methodology. It recognises that the application of geoethical principles must respond to the operational, legal, institutional, cultural, environmental, and social-ecological characteristics of each investigation. Rather than imposing a uniform procedural model, pragmatism supports proportionate, context-sensitive, and adaptable action while maintaining consistency with the foundational principles established in Layer 1 (Fig. 1).

Together, these three pillars enable AGIF to accommodate differences among investigative and legal systems—including adversarial, inquisitorial, hybrid, religious, and customary traditions—without treating ethical standards as entirely context-dependent. The RGP methodology therefore mediates between normative consistency and contextual adaptability, providing the conceptual basis through which universal geoethical commitments can inform practical forensic decision-making.

8.3 Layer 3. Forensic implementation: Adaptive process for ethical geo-investigations

The third layer translates the geoethical foundations and RGP methodology into an operational process for forensic geoscience investigations (Fig. 1). It consists of five interconnected stages: Context; Ethical/Epistemic Issues; Actors/Competencies; Decisions/Actions; and Evaluation/Reflection. These stages are conceived as an adaptive and iterative cycle rather than as a rigid linear sequence.

The first stage, Context, requires an understanding of the operational and social-ecological setting in which the investigation takes place. This includes relevant geological and environmental conditions as well as institutional, legal, cultural, organisational, and societal factors that may influence the investigation and the interpretation or use of scientific evidence.

The second stage, Ethical/Epistemic Issues, identifies the ethical challenges, risks, competing values, knowledge limitations, and uncertainties associated with the investigation.

The third stage, Actors/Competencies, maps the stakeholders and professional actors involved in or affected by the investigation and identifies the competencies required for responsible practice. Competence is understood not only in technical terms but also as the capacity to recognise ethical responsibilities, communicate across disciplinary and institutional boundaries, understand different roles and perspectives, and engage appropriately with uncertainty and competing interests.

The fourth stage, Decisions/Actions, concerns the design and implementation of proportionate and ethically justified investigative actions. Decisions should integrate scientific evidence, ethical principles, contextual constraints, stakeholder responsibilities, and the potential consequences of alternative courses of action. This stage therefore represents the point at which geoethical reasoning becomes operational practice.

The fifth stage, Evaluation/Reflection, assesses the outcomes of investigative decisions and actions and considers whether they remain scientifically robust, ethically defensible, and appropriate to the context. Reflection enables lessons to be incorporated into subsequent stages or future investigations, making the framework explicitly iterative. Evaluation is therefore not simply an endpoint but a feedback mechanism through which investigative practice, professional competence, and ethical judgement can be progressively strengthened.

Across all three layers, Forensic Ethical Literacy functions as a cross-cutting capacity rather than as an additional sequential stage. As represented by the horizontal axis in the framework, it connects geoethical foundations, RGP methodology and forensic implementation.

8.4 Operationalising Layer 3: The five-phase adaptive process

The five phases of Layer 3 operationalise the interaction between the geoethical foundations established in Layer 1 and the RGP methodology introduced in Layer 2 (Fig. 1). They provide a structured but non-prescriptive process through which ethical and epistemic considerations can be incorporated into forensic geoscience investigations and into the education and training of the professionals involved. The phases should not be understood as a rigid procedural sequence. They form an iterative cycle in which contextual assessment, ethical and epistemic analysis, competency

requirements, decisions and actions, and subsequent reflection continuously inform one another. The RGP pillars of Geoscience, Relationality, and Pragmatism, guide reasoning throughout this process, while Forensic Ethical Literacy provides the cross-cutting capacity required to recognise, interpret, and respond to ethical and epistemic challenges at each stage.

8.4.1 Phase 1. Context

The first phase consists of analysing the operational and social-ecological environment in which a forensic geoscience investigation takes place. This includes consideration of landscape and geological characteristics, environmental conditions, predominant crime patterns, legal frameworks, judicial traditions, cultural values, institutional organisation, available scientific resources, and the operational structure of investigative agencies.

Context assessment extends beyond the physical characteristics of the investigative environment. Particular attention should be given to understanding how scientific evidence is generated, communicated, challenged, interpreted, and ultimately evaluated within the relevant justice system. The institutional position of forensic experts, their relationship with investigative and judicial authorities, and the mechanisms through which uncertainty and competing scientific interpretations are addressed may differ substantially between jurisdictions.

In adversarial legal systems, for example, particular attention may be required regarding scientific independence, expert witness responsibilities, transparent reporting, communication of uncertainty, the presentation and challenge of evidence under cross-examination, and the experts overriding duty to the court. In inquisitorial systems, greater emphasis may be placed on interactions between experts and judicial authorities, court-appointed expertise, and the integration of scientific findings within investigative and judicial decision-making. In jurisdictions influenced by religious or customary law, additional considerations may arise in relation to cultural sensitivities, burial practices, sacred landscapes, community engagement, and the treatment of human remains, while maintaining scientific integrity and respect for fundamental human rights.

The purpose of this phase is therefore not simply to describe the setting of an investigation, but to identify the contextual conditions that shape the production, interpretation, communication, and use of geoscientific evidence. In educational applications of the Adaptive Geoethical Investigation Framework (AGIF), the same analysis establishes the contextual conditions within which geoethical education and professional training should be designed.

8.4.2 Phase 2. Ethical/Epistemic issues

Once the context has been established, the second phase identifies the principal ethical and epistemic issues associated with the investigation. This represents an important extension beyond a conventional ethical needs assessment: ethical vulnerabilities cannot always be separated from questions concerning production, reliability, interpretation, limitations, and communication of scientific knowledge.

Particular attention should therefore be given to decisions concerning crime scene detection and management, evidence preservation and recovery, sampling strategies, requests for scientific expertise, analytical choices, interpretation of forensic evidence, communication among disciplines, reporting of uncertainty, and the subsequent investigative or judicial use of scientific findings.

The epistemic dimension requires explicit consideration of what is known, how it is known, what remains uncertain, and how strongly the available evidence supports particular interpretations. In forensic geoscience, such questions are especially significant because geological and environmental evidence may be heterogeneous, spatially variable, incomplete, altered by natural or anthropogenic processes, or susceptible to more than one scientifically plausible interpretation.

This phase therefore seeks to identify points at which ethical vulnerabilities and epistemic limitations may interact. Examples include overstating the strength of an association, failing to communicate uncertainty, inappropriate sampling, confirmation bias, insufficient consideration of alternative hypotheses, or investigative decisions made without the necessary scientific expertise. From an educational perspective, identifying these issues allows training priorities to be directed towards the points in the investigative process where ethical judgement, scientific reasoning, and communication are most consequential.

8.4.3 Phase 3. Actors/Competencies

The third phase maps the actors involved in, responsible for, or affected by the investigative process and identifies the scientific, ethical, professional, and communicative competencies required for their respective roles.

Forensic investigations involve an ecosystem of actors whose responsibilities, authority, scientific knowledge, and relationship to evidence differ substantially. These may include investigators, law enforcement officers, crime scene personnel, forensic scientists and geoscientists, prosecutors, defence lawyers, judges, policy makers, institutional leaders, and other scientific or technical experts. Where judicial systems rely on juries, the role of individual citizens in evaluating scientific evidence should also be considered.

Competency mapping should therefore distinguish between competencies that are shared across the investigative ecosystem and those that are role-specific. Common competencies may include scientific reasoning, ethical judgement, recognition and communication of uncertainty, interdisciplinary collaboration, cultural awareness, critical evaluation of evidence, and evidence-based decision-making. More specialised competencies will depend on the responsibilities and authority of each actor. The relational dimension of RGP is particularly relevant at this stage. Competence is not understood solely as individual technical expertise, but also as the capacity to recognise professional boundaries, determine when additional expertise is required, communicate effectively across disciplinary and institutional interfaces, and understand how one's decisions may affect other actors and the integrity of the investigative process as a whole. In educational applications, this phase enables the definition of differentiated learning outcomes while maintaining a common geoethical foundation across the investigative ecosystem.

8.4.4 *Phase 4. Decisions/Actions*

The fourth phase translates the preceding analysis into proportionate and ethically justified decisions and actions. This is the stage at which scientific understanding, ethical principles, epistemic limitations, contextual factors, stakeholder responsibilities, and practical constraints converge in operational decision-making. Decisions may concern, for example, whether and when specialist geoscientific expertise should be requested; how a scene should be examined; what samples should be collected and preserved; which analytical approaches are appropriate; how competing hypotheses should be evaluated; how uncertainty should be reported; and how scientific findings should inform subsequent investigative or judicial decisions.

The principle of proportionality is especially important at this stage. The scientifically most comprehensive action is not necessarily the most appropriate in every circumstance, just as operational convenience cannot justify compromising scientific integrity or fundamental ethical responsibilities. Decisions should therefore be defensible in relation to the quality of the available evidence, the significance of the investigative question, available resources, potential consequences, and the rights and interests of those affected.

Pragmatism, within the RGP methodology, supports this process by encouraging context-sensitive and adaptable action without reducing ethical judgement to expediency. Adaptation should remain bounded by the foundational principles and geoethical domains established in Layer 1. For educational purposes, this phase translates identified competencies into learning activities capable of developing decision-making in realistic contexts. Training may combine theoretical instruction with interdisciplinary exercises, scenario-based learning, case studies, crime scene simulations, and interaction between scientific experts and investigative personnel. The objective is not merely to transmit ethical rules but to develop the ability to apply them when confronted with uncertainty, competing priorities, institutional constraints, and real-world investigative decisions.

8.4.5 *Phase 5. Evaluation/Reflection*

The fifth phase evaluates the outcomes of decisions and actions and introduces a structured process of reflection and learning. Evaluation should consider not only whether an investigative objective was achieved, but also whether the scientific reasoning was robust, uncertainty was appropriately managed and communicated, relevant expertise was used effectively, interdisciplinary interactions functioned appropriately, and decisions remained consistent with the geoethical principles of the framework. Reflection is essential because forensic investigations operate within changing scientific, technological, legal, environmental, and societal conditions. New analytical technologies may alter what can be inferred from evidence; legislative changes may modify professional responsibilities; emerging crime patterns may create new investigative requirements; and experience from previous cases may reveal previously unrecognised ethical or epistemic vulnerabilities. Evaluation should therefore generate feedback capable of modifying subsequent contextual assessments, identifying new ethical or epistemic issues, refining competency requirements, and improving future decisions and actions. This feedback mechanism explains the cyclical structure of Layer 3: evaluation is not an endpoint but a mechanism through which the entire investigative system can learn and adapt.

The same principle applies to geoethical education. Training programmes should be periodically reviewed in response to scientific innovation, technological developments, legislative change, emerging crime patterns, societal expectations, and operational experience. Evaluation should assess not only knowledge acquisition but also the quality of decision-making, interdisciplinary collaboration, communication of scientific evidence and uncertainty, and the practical application of geoethical principles in real or simulated investigative environments.

Together, these five phases establish a continuous cycle linking context, ethical and epistemic awareness, actors and competencies, decisions and actions, and evaluation and reflection. The cycle enables AGIF to respond to changes in forensic science, investigative practice, technological innovation, legal systems, environmental conditions, and societal expectations without abandoning its foundational ethical commitments. This distinction is central to the architecture of AGIF. Layer 1 provides normative orientation, establishing the principles, values, and domains of responsibility that define ethically responsible forensic geoscience. Layer 2 provides methodological orientation, using Geoscience, Relationality, and Pragmatism to mediate between universal commitments and contextual realities. Layer 3 provides operational orientation, translating these foundations into an adaptive cycle of investigation, decision-making, evaluation, and learning.

Within this architecture, Forensic Ethical Literacy is not confined to Phase 4 or to formal educational programmes. Rather, it operates across all three layers and throughout all five phases as the capacity to recognise ethical and epistemic dimensions of forensic problems, understand the capabilities and limitations of scientific evidence, identify when specialised expertise is required, communicate effectively across disciplines, critically evaluate uncertainty and competing interpretations, reflect on professional and institutional responsibilities, and make ethically informed decisions. Geoethical education can consequently be understood as one of the principal mechanisms through which Forensic Ethical Literacy is developed and sustained. Educational programmes derived from AGIF should therefore be adapted to the roles, competencies, legal settings, environmental conditions, and operational realities identified through the framework, while remaining anchored in its shared geoethical foundations.

AGIF thus provides a flexible architecture through which countries and institutions operating within diverse geological, environmental, cultural, institutional, and legal contexts can develop context-sensitive investigative practices and educational programmes while maintaining a common commitment to geoethical principles. By integrating geoethical foundations, the RGP methodology, adaptive forensic implementation, and Forensic Ethical Literacy within a single conceptual model, the framework provides a pathway for embedding process ethics throughout the forensic investigative ecosystem. Rather than treating ethics as an external set of rules applied after scientific decisions have been made, AGIF

positions ethical and epistemic reasoning as integral to the entire process through which forensic knowledge is produced, interpreted, communicated, used, and evaluated. In doing so, the framework demonstrates how shared geoethical commitments can support forensic geoscience practices that are scientifically rigorous, epistemically responsible, ethically defensible, context-sensitive, and socially responsible across diverse systems of justice.

8.5 Illustrative application of AGIF: A hypothetical search for clandestinely buried human remains

The practical logic of AGIF can be illustrated through a hypothetical investigation involving the suspected clandestine burial of human remains in a semi-rural area. The example is intended solely to demonstrate how the five implementation phases may interact in practice and does not constitute empirical validation of the framework.

1. Context.

Investigators receive information indicating that human remains may have been clandestinely buried in an area containing woodland, disturbed ground, and several former excavation pits. The information is incomplete and includes an approximate location rather than a precisely identified burial site. Before selecting investigative methods, the team considers the geological and environmental setting, including soil characteristics, vegetation, surface morphology, drainage conditions, and previous land disturbance. Site accessibility, ownership, weather conditions, available resources, relevant legal requirements, and restrictions concerning disturbance of the ground are also considered.

At this stage, the team avoids treating the reported location as an established burial site. The available information is recorded as provisional, together with its sources, reliability, and uncertainties.

2. Ethical and epistemic issues.

The team identifies several interconnected ethical and epistemic issues. The information concerning the suspected burial is uncertain, and the absence of a detectable anomaly cannot be assumed to demonstrate the absence of human remains. Conversely, an anomalous geophysical or remote-sensing signal cannot by itself establish the presence of a burial.

The investigators therefore consider the potential consequences of different investigative choices. An unnecessarily invasive intervention could disturb or destroy evidence, while an overly cautious approach could leave relevant evidence undetected. The team also considers the need to avoid confirmation bias, to distinguish observations from interpretations, and to communicate the limitations of each method clearly to investigators and other stakeholders.

These considerations lead the team to formulate explicit questions: What information is sufficiently reliable to guide the next decision What uncertainties remain unresolved Which investigative action is proportionate to the available evidence and least likely to compromise potentially relevant evidence

3. Actors and competencies.

The investigation involves several actors with complementary responsibilities. A forensic geoscientist contributes knowledge of the geological and environmental setting and advises on the suitability and limitations of geophysical or other geoscientific approaches. Crime-scene personnel contribute expertise concerning evidence preservation and documentation. Investigators provide information concerning the investigative context and legal requirements, while a forensic anthropologist may advise on the implications of possible human remains and subsequent recovery and examination.

The team explicitly identifies what each participant knows, what remains uncertain, and which decisions fall within each professional domain. This helps prevent technical expertise from being treated as interchangeable with investigative authority and clarifies responsibility for significant decisions.

4. Decisions and actions.

Considering the contextual information, identified uncertainties, available expertise, and constraints, the team decides to begin with non-invasive geoscientific investigation rather than immediate excavation. The initial survey is designed to test specific hypotheses about possible ground disturbance while preserving the integrity of the site.

The results reveal several anomalies, but they do not produce a single unambiguous signature consistent with a clandestine burial. Some anomalies correspond to known geological or anthropogenic features, while others remain difficult to interpret. Rather than treating the anomalous signals as confirmation of the original hypothesis, the team revisits the assumptions underlying the investigation.

Additional information subsequently becomes available concerning previous land use at the site. This information changes the interpretation of some of the anomalies and reduces confidence in one of the initial target areas. The team therefore modifies the investigative strategy and prioritises areas where the combined evidence provides a stronger rationale for further investigation.

Throughout this process, decisions are documented together with the evidence considered, the uncertainties identified, the professional judgements involved, and the reasons for selecting one investigative action over alternatives.

5. Evaluation and reflection.

The results are evaluated against the initial assumptions and decision rationale. The investigation does not initially produce conclusive evidence of human remains. However, the process reveals that some of the original assumptions were insufficiently supported and that several observed anomalies had alternative explanations.

The team therefore returns to earlier stages of the framework. The contextual assessment is updated, the epistemic status of the available evidence is reassessed, and the roles of the different specialists are reconsidered in light of the new information. If further investigation is warranted, subsequent actions are selected on the basis of this revised understanding rather than simply continuing the original investigative sequence.

This iterative process illustrates a central feature of AGIF: an investigative decision is not treated as final merely because it has already been made. New evidence, unexpected findings, stakeholder input, or critical reflection may alter the interpretation of the situation and justify revisiting earlier decisions.

In this example, Forensic Ethical Literacy operates across all five phases rather than constituting a separate procedural step. It supports the capacity of participants to recognise

uncertainty, identify ethical implications, understand the limits of their own expertise, communicate those limits to others, distinguish evidence from interpretation, and reflect critically on the consequences of investigative decisions.

The example therefore illustrates how AGIF connects context, ethical and epistemic reasoning, actors and competencies, decisions and actions, and evaluation and reflection within an adaptive investigative process. Its purpose is not to prescribe a fixed sequence of technical procedures, but to provide a structured basis for responsible judgement in situations characterised by uncertainty, multiple actors, competing considerations, and evolving evidence.

9 Conclusions

This paper argues that the continued development of forensic geoscience requires a corresponding expansion of geoethical thinking and ethical reasoning across the wider forensic investigative ecosystem. Existing geoethical frameworks provide an essential foundation through their emphasis on scientific integrity, competence, impartiality, transparency, accountability, and responsibility to society and the environment. However, contemporary forensic investigations involve many and complex processes in which evidence is generated, recovered, interpreted, communicated, challenged, evaluated, and ultimately applied by multiple actors. Ethical responsibility therefore extends beyond individual practitioners to encompass the interconnected relationships, decisions, and institutional structures through which forensic knowledge acquires investigative and judicial significance.

This perspective broadens geoethics from a focus on professional conduct to a process-oriented understanding of ethical and epistemic responsibility. Although individual responsibility remains fundamental, scientific evidence can contribute effectively to justice only when the processes surrounding its production and use are themselves ethically robust. These processes include identifying evidential needs and priorities, evidence recovery and preservation, interpretation, communication of uncertainty, interdisciplinary collaboration, decision-making, and critical reflection.

To support this broader perspective, the paper introduces the AGIF and the concept of Forensic Ethical Literacy. AGIF integrates three interconnected dimensions. Geoethical Foundations provide the normative basis of responsible practice. Relational Geoscientific Pragmatism offers a methodological approach for interpreting geoethical commitments within specific contexts. Forensic Implementation operationalises these principles through iterative consideration of context, ethical and epistemic issues, actors and competencies, decisions and actions, and evaluation and reflection. Together, these dimensions form a flexible conceptual architecture that can be adapted to diverse geological, environmental, cultural, institutional, and legal settings while maintaining coherence with shared geoethical commitments.

Forensic Ethical Literacy functions as the framework's integrative capability, encompassing ethical awareness, critical judgement, reflexivity, epistemic responsibility, scientific understanding, and responsible action. Its relevance extends beyond geoscientists to all individuals whose decisions influence the production, interpretation, communication, evaluation, or application of forensic evidence. AGIF is not intended to prescribe procedure or replace professional codes, accreditation systems, quality standards, or legal requirements. Rather, it provides a structured framework for critical reflection on investigative and organisational processes and for connecting these processes within a shared geoethical orientation.

As a conceptual framework, AGIF requires further development and empirical evaluation. Future research should examine its application across different forensic geoscience domains, institutional settings, and justice systems, while exploring methods for assessing ethical and epistemic reasoning in both education and professional practice. Such work will help determine whether the framework improves the recognition of ethical vulnerabilities, supports more effective communication of uncertainty, strengthens interdisciplinary decision-making, and enhances reflexivity regarding the consequences of investigative actions.

The principal contribution of this paper is the integration of geoethical principles, RGP, and Forensic Ethical Literacy into a coherent framework for embedding ethical and epistemic reasoning throughout forensic geoscience processes. By extending geoethics beyond individual professional conduct to encompass the broader processes through which geoscientific knowledge is generated, interpreted, communicated, evaluated, and applied, the AGIF offers a conceptual foundation for forensic practice that is scientifically rigorous, epistemically responsible, ethically defensible, and socially responsive.

Author contribution statement

Lorna A. Dawson, Rosa Maria Di Maggio: Conceptualization, methodology, writing original draft, writing–review & editing; Silvia Peppoloni: Conceptual diagram, conceptualization, methodology, writing original draft, writing–review & editing.

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Declaration of competing interest

All the contributing authors report no conflict of interest in this work.

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Not applicable.

Use of AI statement

During the preparation of this work, the authors used ChatGPT in order to compile the figure. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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