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The challenges of signal interpretation of burials in ground-penetrating radar

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Abstract

The identification of unmarked graves and burials is one of most common applications of ground-penetrating radar (GPR) in archaeology. Despite a high frequency of use and a long history of experimentation, there appears to be considerable variability on what indicates a burial in GPR data—likely a consequence of heterogeneity in geological contexts, age and in burial practices. Although general statements about uncertainty in GPR interpretation may be acceptable in archaeological applications, the interpretative process becomes more complicated when GPR is used to locate unmarked graves in culturally, politically and legally contested locations such as at former Indian Residential Schools (IRSs) in Canada. In this paper, we review international applications of the technique and identify trends and traits between the authors' use of GPR to identify burials. By categorizing the studies based on the GPR reflection signatures identified, our review demonstrates that there is modest consensus across the 77 documents reviewed for what represents a burial. Interrogating these findings, we identify a range of potential contributors to signal heterogeneity and outline potential steps forward to a higher confidence or more statistically robust identification of unmarked graves using GPR.

KEYWORDS
archaeology, burial investigations, geophysical methods, ground-penetrating radar, uncertainty

1 | INTRODUCTION

Archaeologists tend to employ methods such as ground-penetrating radar (GPR) when they work as expected and discard them when they do not, limiting published analyses to the subset of successful applications, which may be in the minority (Jones, 2008). When the method is asked to work beyond the boundaries of established parameters of success, archaeological approaches benefit from greater logical formality (Kvamme, 2003). This issue has become acute in Canada in recent years regarding the application GPR for the identification of human burials[1] because this method is now being employed in the difficult task of locating missing children from Indian Residential Schools (IRSs) often outside of formal cemeteries.

As was determined by Truth and Reconciliation Commission of Canada (TRC, 2015), over 150 000 Indigenous children were forced to attend IRS between the 1860s and 1996, when the last school (Muskowekwan IRS near Regina, Saskatchewan) closed. Over 4000

[1]The terms 'burial' and 'grave' are often used synonymously. We use 'burial' to refer to an intentional place where someone is buried (i.e., formally) and 'grave' to refer to the physical properties of the burial.

children are known to have died from neglect, malnutrition, violence and trauma; and Murray Sinclair, former Commissioner of the TRC, estimates the actual number could be 10 or 15 times greater. Many of these children are missing—their final resting places unknown. Some, though not all, are in unmarked terrestrial graves. Some of these are in formal cemeteries, but many are in less formal and sometimes clandestine burials. Since the discovery of unmarked graves at the Kamloops IRS in 2021, federal and provincial governments in Canada have supported efforts by Indigenous communities to located unmarked graves of missing children in IRS landscapes. Many are using GPR to explore potential burial locations, based on the success of GPR for locating burials in formal cemeteries (see, e.g., Wadsworth et al., 2021). In IRS landscapes, the method is being asked to locate poorly defined targets in complex geological contexts, both of which extend the method beyond the current sample of successful examples. Other methods, such as electromagnetic (EM) induction (Bigman, 2012), have value and combining multiple methods may provide superior results (Gaffney et al., 2015; Green, 2020; Nobes, 1999; Pringle et al., 2012), though we focus here only on GPR.

A core challenge of the application of GPR to such landscapes is the multiple users of and audiences for this technology. An emerging consensus in Canadian politics[2] is that the ground searches for missing children are most appropriately conducted by Indigenous communities themselves—a process that will require training and translation. Geophysicists have developed a technical language and sub-disciplinary framework that advances scholarship but can be exclusionary to non-experts. Archaeologists apply GPR and work in partnership with Indigenous and other communities but often lack geophysical expertise (see, e.g., Ferguson et al., 2021). In this paper, we attempt to reach all audiences by (1) attending to the core geophysical principles and current scholarship to identify a current omission: the lack of a representative sample of GPR signal variability from all known grave/burial contexts, (2) translating these principles to non-expert audiences and (3) anticipating the needs of ground search teams who may use GPR effectively but lack geophysical training. The reality is that there is currently insufficient geophysical capacity in Canada to undertake the search for missing children; this requires a collective effort between all three user-groups.

GPR was developed as a modified version of airborne radar applied to the near surface of the ground where it tended to be useful at locating highly visible (i.e., large, shallow, organized and reflective) targets[3] against muted (i.e., low reflectivity) backgrounds (Fiedler et al., 2009). Its value in North American archaeology was demonstrated early in its modern history when researchers began compiling examples of GPR results that conformed to other data sets, typically from excavation (e.g., Bevan, 1991; Conyers, 2013; Vaughan, 1986; Whiting et al., 2001). Early researchers, notably Bevan (1991), Conyers (2013) and Goodman and Piro (2013) reviewed the principles of GPR operation, the geophysical theory at its root and proposals of best practices with examples of both successful interpretation and areas of potential complexity. Bevan (1991), for example, noted that the GPR reflected signal of a burial was largely mediated by higher moisture content within the disturbed soils of a grave shaft especially when contrasted with stratigraphic patterns of the geological context (see also Cannell et al., 2018; Cavalcanti et al., 2018; Doolittle & Bellantoni, 2010; Molina et al., 2016; Sherrod et al., 2020). Pringle et al. (2020) note from experiments that pig cadavers wrapped in fabric or in caskets produce stronger GPR signal than without these treatments, possibly a consequence of different moisture regimes and consequent dielectric contrasts (Sherrod et al., 2020). Conyers (2013) developed a guide to interpretation focused on a merging of theory and examples; Goodman developed simulation (GPR Sim) and advanced processing software (GPR Slice) to aid in developing interpretable results. These efforts are now standards in the field. What they could not do given the general framing of their exploration of GPR in field studies, is provide complete guidance on the range of variation within specific target classes or the effect of complex landscapes (Schultz & Martin, 2012).

Identification of burials is a common application of GPR, but one that, by the nature of its setting, often tends to preclude the need for identifying specific GPR traits. We use the word 'trait' to refer to GPR signature associated with burials, defined as distinctive reflection or amplitude patterns seen in profile or depth-slice map view; our language is analogous to its use in biology as the phenotypic expression of a genotypic code. Specifically, formal, historic cemeteries are the most common context for such work, and these are typically located in places where the hand-digging of graves was facilitated by fine-grained, relatively homogenous sediments such as sands and gravels. Areas with high clay deposits, boulders or near-surface bedrock were likely avoided because they are impediments to grave digging. Cemeteries from these types of sedimentary settings tend to have low conductivity (especially the sands) and usually lack large lateral and vertical inhomogeneities that might complicate GPR interpretation.

Other factors that tend to facilitate GPR-based grave interpretations in cemeteries include the organized alignment of graves in rows, the presence of diagnostic topography such as mounds or depressions and the typical presence of at least some grave markers. The upshot is that any GPR signature of grave-like size, especially in depth slices, is likely to be a grave—or more precisely the column of disordered sediment in the grave shaft that contains higher water content as a result of capillary action through the voids in the disturbed soil (Bevan, 1991). As a result, burial identification in formal cemeteries with GPR is relatively unambiguous and focuses on the identification of a discontinuity of the appropriate size, shape, orientation and location in the soil matrix rather than on specific traits in GPR data (although see Conyers, 2013).

When GPR is applied in less-formal contexts, many of the above facilitating factors are absent (see, e.g., Fernández-Álvarez et al., 2016). For example, burials outside of cemeteries can be emplaced in complex and heterogenous geological contexts containing potentially confusing features, possibly within a noisier background (Schultz & Martin, 2012).

[2]See the National Advisory Committee on Missing Children and unmarked Burials (www.nac-cnn.ca) and the Office of the Special Interlocutor (www.osi-bis.ca) for details.

[3]The language of archaeology and geophysics can translate poorly into conversations about missing loved ones. Traditionally, we would call an undefined signal of interest an 'anomaly' because it is definable by its difference, hence anomalous. 'Target' is preferred by some, although it has a specific use as the GPR qualities of a known category of feature. We tend to refer to potential signals as targets and known signal as ancestors, though we expect the technical language will continue to adapt through use.

In addition, sites with thick clay-mineral deposits will tend to be highly conductive, limiting the depth of GPR signal penetration and often introducing artefacts to the data such as ringing or air waves that tend to confound interpretations. In addition, the absence of order, consistent shape and additional lines of non-GPR evidence further challenge interpretation. Under such conditions, identification of suspected burials will necessarily rely much more heavily on interpretations of specific GPR signatures. However, as discussed below, our survey of published literature indicates that the possible range of GPR traits of burials is greater than expected ($n = 23$) and inconsistently present in the literature (only one trait occurring +50% of reported results). The challenge ahead is to define the specific correlations between geophysical patterns of graves and GPR results and to parse these by (1) geological context, (2) grave shape and (3) grave contents, all in relation to factors such as dielectric contrast and conductivity that give rise to specific reflection and amplitude patterns in map and profile view. In this paper, we explore what is known from the current published sample of results and synthesize a summary of common ground in existing work and possible directions for further work.

2 | METHODS

2.1 | GPR overview

A brief review of the origin of GPR radargrams and amplitude maps is useful to enable better understanding of the potential issues involved in interpretation that are discussed in this manuscript. In a typical archaeological geophysics application, pulsed GPR energy, normally in the range of 200–800 MHz, propagates into the ground from a ground-coupled transmitting antenna. Although GPR propagation is a complex EM phenomenon, GPR transmission in the subsurface may be treated as a wave phenomenon, subject to various assumptions (e.g., Annan, 2002; Conyers, 2013; Goodman & Piro, 2013). The wave-based approach is also the basis for GPR processing software, which is based on seismic-reflection processing software.

Where downward GPR energy encounters an interface with a change in EM properties, specifically dielectric constant (or dielectric, or relative permittivity), some energy is reflected towards the surface, while the remainder continues downward. GPR energy propagates downward in an elongated 'beam' that has an elliptical footprint on a hypothetical horizontal subsurface interface. Thus, GPR may detect dielectric contrasts to the sides, front and back of the downward continuation of the transmitting antenna. In addition to dielectric (and directly related velocity), the behaviour of GPR energy in the subsurface is strongly controlled by conductivity. In terms of earth materials, salt water and certain clay minerals are highly conductive, which results in strong attenuation of GPR energy. On the other hand, ice, fresh water and dry sand all have low to extremely low conductivity and as such attenuate GPR energy much less.

Reflection amplitude depends on the angle of incidence as well as on the contrast in dielectric across the interface. Incoming reflections from the subsurface interfaces are received by the receiving antenna, then recorded on the field computer. A single cycle of pulse and recorded energy returns is recorded as amplitude (and sign) versus time (in ns). Typically, a number of pulses are sent out from the transmitted in extremely rapid succession at one spot, resulting in a 'stacked' (another borrowing from the seismic industry) single GPR trace (also known as an A-scan). This process is repeated using a predefined time or distance interval until the survey profile is complete. A single profile, which is a collection of dozens to thousands of A-scans, is termed a B-scan or radargram.

A typical GPR survey for unmarked graves involves surveying in closely spaced, parallel lines. Sometimes, these are in one compass direction only (a Y survey), while two different perpendicular sets of profiles may be collected in an XY survey. In the office, a specialist GPR software applies filtering, geometric corrections and various enhancements (all having analogues in the seismic data-processing world) to improve the interpretation of radargrams. Finally, processed radargrams may be assembled into 3D volumes and then sliced depth-wise at arbitrarily depth intervals for map-based interpretation. These map-view depth slices may also be called C-scans, amplitude maps or time-slice maps. Most users rely on radargrams and amplitude maps for visual interpretation. Amplitude maps may be exported from GPR software into geographic information system (GIS) software for overall comparison with related data sets such as LiDAR and orthoimagery. Radargram interpretations are generally performed within purpose-built GPR software, with the possibility to export interpretations to GIS-ready maps or profiles.

Radargrams contain patterns of the reflected electromagnetic (EM) signal that are well described (Conyers, 2013 is an accessible source). EM waves pass through different materials at different velocities (a trait known as their relative permittivity); air and water are at the extremes of permittivity in materials encountered in the near subsurface of the ground with the signal moving faster through air than water. When crossing a boundary between materials of different permittivity, parts of the wave are reflected to the sensor (reflection), while others continue (transmit) or change direction (refraction), and the remaining signal is absorbed. The shape and size of the boundary as well as the angle of incidence of transmitted wave to the boundary influence these patterns. The GPR signal is generated and received spherically but is plotted as though the signal is reflected from directly below the array. Each of these factors can influence how a subsurface pattern appears in a radargram visualization.

The broader interest in GPR as a method for locating unmarked graves generates its own challenges. IRS survivors have reported discomfort with the language of geoscience, specifically the use of 'anomaly' to indicate a potential unmarked burial of their relatives. The language of science can be culturally oriented and distancing, and we encourage users to consider the implications of their use of terms from geoscience in the search for missing children. However, a revision of this nature is beyond the scope of this paper. Thus, we refer to patterns of difference as targets or anomalies and visualizations of GPR results as radargrams (aka profile views and radar profiles) and amplitude maps (plan views, sometimes referred to as time-slice maps or depth slices) (see also Annan, 2002). While amplitude maps provide useful guidance and can illustrate important subsurface patterns,

TABLE 1 GPR traits of burials identified as traits in B-scans.

Types of traits	Burial trait	GPR signal trait	Source
Grave shaft	Upper transition of grave shaft	Planar transition	Almeida et al. (2016); Aziz et al. (2016); Conyers (2013, p. 132); Goodman and Piro (2013)
	Lower transition of grave shaft/water	Planar transition, signal concentration and tabletop reflection	Almeida et al. (2016); Aziz et al. (2016); Bevan (1991); Carcione et al. (2017); Conyers (2013, p. 136); Leach (2021, p. 63); Doolittle and Bellantoni (2010); Goodman and Piro (2013)
	Short axis vertical transitions of grave shaft	Vertical discontinuity with hyperbolic elements; Barone et al. (2016) argue it looks like two hyperbolic events separated by a planar reflective transition	Bagaskara et al. (2021); Barone et al. (2016); Bevan (1991); Conyers (2013, pp. 132, 133); Dick et al. (2017); Doolittle and Bellantoni (2010); Goodman and Piro (2013); Molina et al. (2015)
	Long axis vertical transition of grave shaft	Vertical discontinuity with hyperbolic elements	Conyers (2013, pp. 132, 133)
	Grave shaft shoulders	Single interior hyperbolic tails	Leach (2021, p. 10); Goodman and Piro (2013); Molina et al. (2015)
	Stratigraphic discontinuity/grave shaft/backfill	Lateral discontinuity of either greater signal within or outside of grave, depending on sediments, may include polarity inversion of the amplitude	Almeida et al. (2016); Bagaskara et al. (2021); Bevan (1991); Büyüksaraç et al. (2014); Cannell et al. (2018); Conyers (2013, p. 132); Damiata et al. (2017); Doolittle and Bellantoni (2010); Downs et al. (2020); Ferguson et al. (2021); Fernández-Álvarez et al. (2016); Fiedler et al. (2009); Gaffney et al. (2015); Gavin et al. (2014); Goodman and Piro (2013); Hansen et al. (2014); Honerkamp and Crook (2012); Ibrahim and Ebraheem (2020); King et al. (1993); Koppenjan et al. (2003); Koşaroğlu et al. (2021); Lafferty et al. (2021); Leucci et al. (2016); Lowe and Law (2022); Martin and Everett (2023); Moffat et al. (2020); Nichols (2015); Nobes (1999); Novo et al. (2010); Persico et al. (2019); Polymenakos (2019); Pringle et al. (2008); Różycki et al. (2020); Schmidt et al. (2015); Schultz et al. (2016); Schultz and Martin (2012); Şeren et al. (2017); Sherrod et al. (2020); Sutton and Conyers (2013); Utsi and Colls (2017); van Shoor et al. (2017); Vaughan (1986); Wadsworth et al. (2020, 2021)
Grave contents	Sagging casket slump	Stratigraphic discontinuity	Conyers (2013, p. 135)
	Void of casket	Complex effects including (1) pull up of signal from below, (2) 'X' shape above void and (3) reverse polarity within void	Carcione et al. (2017); Conyers (2013, p. 132)
	Point targets within grave	Hotspots within amplitude maps and dimensional pattern matching grave shaft	Almeida et al. (2016); Bevan (1991); Conyers (2013, pp. 15, 139, 147); Dick et al. (2017); Goodman and Piro (2013); Lafferty et al. (2021); Persico et al. (2019); Polymenakos (2019)
	Metal within grave	Ringing elements within grave	Conyers (2013, p. 151); Lowe and Law (2022)

TABLE 1 (Continued)

Types of traits	Burial trait	GPR signal trait	Source
	Concrete elements	Complex: can be reflective planar effects and reflected wave effects (esp. with voids) and echoes	Aziz et al. (2016); Conyers (2013, p. 137)
	Casket shape	Stratigraphic boundaries (though Conyers, 2013 suggests this might explain the convex wave effect—unlikely)	Conyers (2013, p. 135)
	Differential reflective targets within grave	Clustered hyperbolas	Akinsunmade et al. (2019)
	Water differences	Amplitude contrast	Bagaskara et al. (2021)
	Decomposition	Salt leaching creating reflections	Büyüksaraç et al. (2014); Jones (2008); Mellet (1992)
	Skeletal elements	Diffractions from skeletal remains (long bones and skull appear as hyperbolas)	Almeida et al. (2016); Damiata et al. (2017); Fernández-Álvarez et al. (2016); Hammon et al. (2000)
	Head versus foot	Head is more visible in GPR	Nobes (1999)
	Attenuation	In clay and/or salt rich soils	Hansen et al. (2014)
	Void effect	V-shaped pattern	Conyers (2013); Jol et al. (2002)
Sediment effect	Surface slump	Concavity at surface	Bevan (1991); Conyers (2013, p. 139)
Wave effect	Reflexive space/effect of short axis vertical transitions	Convex wave effect above upper boundary	Aziz et al. (2016); Bagaskara et al. (2021); Conyers (2013, p. 135); Różycki et al. (2020); Utsi and Colls (2017); Wadsworth et al. (2020, 2021)
Diffractive hyperbolic effect	Large difference in dialectric constants between the grave shaft and the surrounding sediment	Long hyperbolic tails from sides of parabolic wave effect/diffraction hyperbola	Aziz et al. (2016); Bevan (1991); Booth and Pringle (2016); Dick et al. (2017); Doolittle and Bellantoni (2010); Downs et al. (2020); Ferguson et al. (2021); Gavin et al. (2014); Goodman and Piro (2013); Hammon et al. (2000); Hansen et al. (2014, p. 144); Ibrahim and Ebraheem (2020); Jol et al. (2002); Jones (2008); Nichols (2015); Nobes (1999); Polymenakos (2019); Różycki et al. (2020); Salsarola et al. (2015); Schultz (2012); Schultz et al. (2016); Schultz and Martin (2012); Sutton and Conyers (2013); van Shoor et al. (2017); Wadsworth et al. (2020, 2021)
Basin-shaped burial	Basin-shaped pit	X-pattern within pit from wave effects with parabolic convex shape beneath	Conyers (2016, pp. 41, 55)

radargrams provide the most detailed and reliable information for target identification.

2.2 | Literature analysis

Our analysis is based on a review of 77 recent publications that explore the identification of burials with GPR (see Table 1). These publications were found through multiple database searches (e.g., SCOPUS, Google Scholar and Web of Science) and are restricted to published materials strictly focused on GPR and unmarked burial identification (not included as part of larger archaeological assessments). Search terms (and their variants) included 'unmarked graves', 'GPR', 'ground-penetrating radar' and 'burials'. Results were restricted to published studies written in English. We note that most of these are archaeological rather than geophysical, a pattern that likely reflects the main field users of GPR or at least the current level of public attention that GPR commands. This creates an important dynamic in which geophysicists typically develop the technology and theoretical scholarship while archaeologists often apply the methods and develop the sample of results that captures the heterogeneity of specific target populations such as graves.

It is notable that few publications discuss processing workflows or GPR parameters in detail (but see Goodman & Piro, 2013; Leach, 2021). Most GPR systems have default settings including for

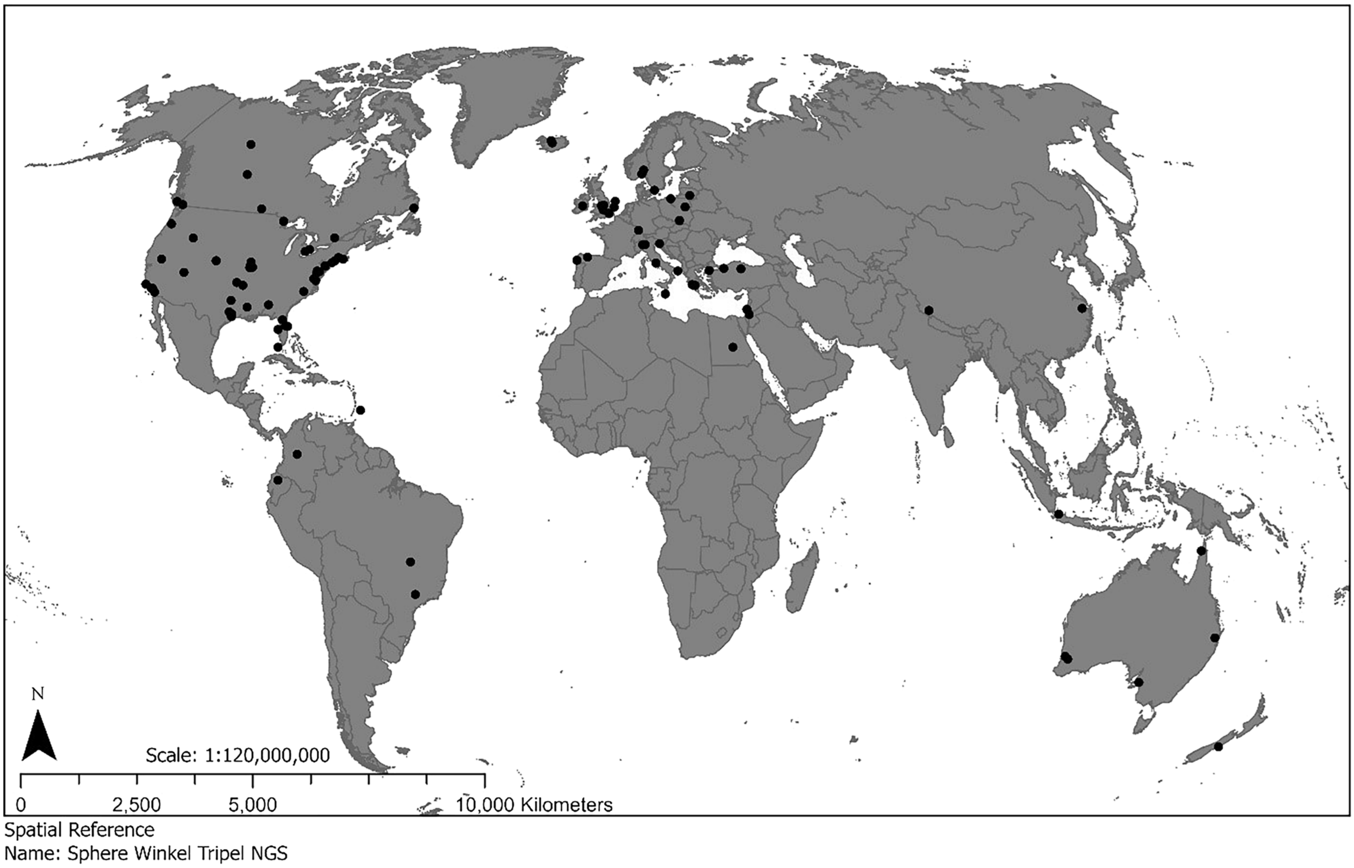

FIGURE 1 The distribution of study locations in cited literature.

gain, filtering and transformations. Methods testing to evaluate the effects of data collection parameters (for work in the field) and the influence of post-processing steps on the visibility of specific target patterns are underdeveloped. Parameter settings and processing options can introduce artefacts or reduce useful information. While beyond the scope of this paper, we note that many users have developed their own well-defined systems for local conditions and that equipment manufacturer defaults tend to work well when searching for large targets in non-complex geologies.

Figure 1 shows the distribution of study locations in the cited literature, and Figure 2 illustrates their distribution over time by date of publication. Much of the literature is skewed towards geological and cultural contexts where geophysicists and archaeologists most commonly live and work: namely North America and Europe. There is a trend towards more GPR analysis of burials over time (Figure 2); Bevan (2000) reports a similar trend in the frequency of geophysical surveys at archaeological sites. The former suggests that current results are not representative of the population of graves or grave contexts, while the latter suggests that representation will improve over time.

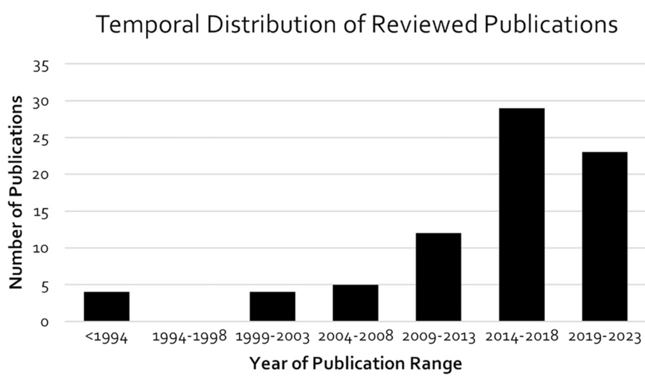

FIGURE 2 The distribution of cited literature in time by date of publication.

3 | RESULTS

Our first observation from this literature review is that few authors explore either the specific nature of GPR traits in local grave identification or refer to such use of GPR in other geologic contexts or locales. They rely instead on either an imprecisely defined composite suite of traits from visualizations or focus instead on single traits as definitive factors for interpretation based on their local sample. It is important to note that this is not a criticism of these works—these analyses are perfectly logical and justifiable within their own specific contexts. A preliminary observation of these data indicates that there are at least 23 GPR visualization traits (and thus potentially a similar or greater number of subsurface patterns) influencing GPR visualizations of burials. We list these in Table 1 and show their frequency

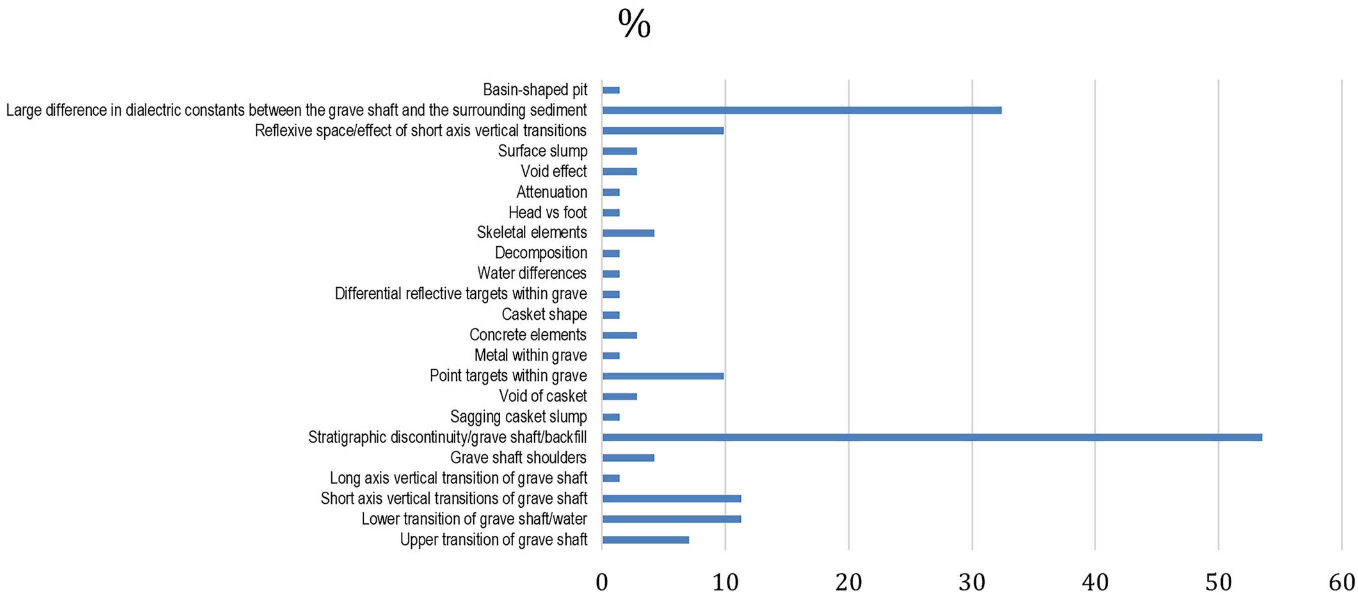

FIGURE 3 Frequency of citation of GPR visualization traits in the identification of burials from sources in Table 1. [Colour figure can be viewed at wileyonlinelibrary.com]

distribution by publication in Figure 3. As we discuss in more detail below, there are clearly numerous traits that may be associated with burials in GPR—likely our result is an incomplete list. Interpretations focusing on either a single trait or a poorly defined suite of traits does not account for the corpus of evidence already assembled in publications. As noted above, this is not a significant impediment to identification of burials in many local cemetery contents. Rather, this variability likely derives from geological variation between sites studied in the various sources; this suggests that local conditions will produce a much smaller suite of correlated traits. The current sample of GPR results is too small to assess the contribution of geological variability to grave identification—and we suggest that researchers conduct assessments of local conditions while reviewing general patterns. The compilation of many local case studies may create both a larger global list of traits and, potentially, correlations between specific traits and contexts, but the data are not yet available for such an analysis (see, e.g., Hansen et al., 2014).

All the traits listed in Table 1 are visible in published radargrams; not all are visible in amplitude maps. As informed by the above description of GPR methods, the signatures described in Table 1 may be sorted into six categories (see Figure 4): (1) those that are responses from the grave shaft itself, (2) those that reflect the grave contents, (3) surface patterns, (4) voids associated with coffins and (5 and 6) two effects generated by wave interference.

As Bevan (1991:1311) noted, the most common trait associated with burials is the discontinuity associated with the grave shaft. While there are many potential differences between the contents of a grave and the surrounding sediments, Bevan suggests that the principal quality that increases GPR reflectivity is moisture, a result of the typically higher water content from the loosening and mixing of sediments during digging and redeposition. Some authors note specific effects of a rectangular grave shaft including high intensity reflections from the upper and lower transitions of this difference within the grave shaft column. GPR reflections can also be accentuated by curving lines into and down the shaft (shoulder effects), a consequence of the reflections emanating from refraction interfaces across the vertical boundary.

Many authors note that the anomalous nature of a grave is relative to its surrounding geological matrix (see, e.g., Nobes, 1999, p. 357). Graves may be dug in a wide range of materials with diverse geological pedological sources and stratigraphic patterns. One feature that consistently defines historical cemeteries, however, is the ability and relative ease of excavating a grave shaft with hand tools. In our experience, there is a clear correlation between cemeteries and silt-, sand- and pebble-rich surficial layers with lesser components of clays and smaller cobbles. From this, it follows that further work on evaluating correlations between cemetery locations and geological settings and between geological settings and GPR grave signatures appears warranted.

Grave contents are a related but distinct suite of traits that typically form smaller targets within a grave shaft. These can include metal parts from coffin hardware, casket patterns such as voids and water variations at the lower boundary of the grave shaft, including those of the interred individual. Some elements of the larger patterns of stratigraphic discontinuity likely overlap with these traits, but only some authors make specific identifications of grave contents. Some authors (such as Almeida et al., 2016; Damiata et al., 2017; Fernández-Álvarez et al., 2016; Hammon et al., 2000) report the identification of skeletal elements in GPR visualizations, especially large elements such as long bones and skulls. Schneider et al. (2018) demonstrate that large mammalian bones have permittivity values different from common sediments in soils, indicating that such identifications are possible. While these are usually thought of as too small to visualize at standard GPR frequencies for grave scans, higher

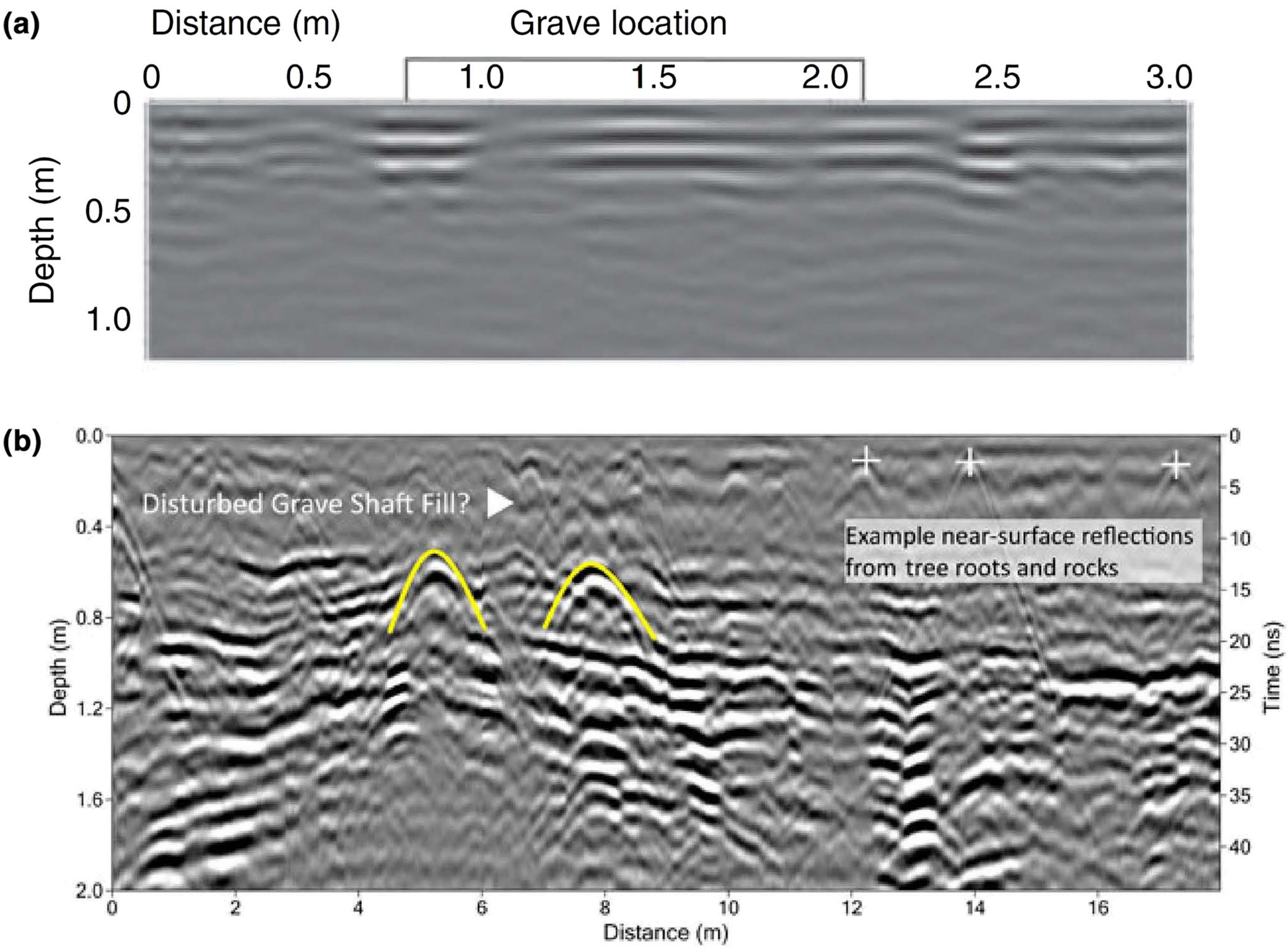

FIGURE 4 Examples of the most common GPR traits of burials from sources in Table 1: (a) stratigraphic discontinuities from a forensic context (Schultz, 2012) and (b) diffractive hyperbolas highlighted (Wadsworth et al., 2021). [Colour figure can be viewed at wileyonlinelibrary.com]

frequencies, shallower depths and potential polarization effects make such identifications possible. However, in most typical cemetery settings, there are many factors that argue against the possibility of direct detection of human bone, including depth of burial, lack of dielectric contrast between bone and typical earth materials and wavelength considerations. While direct bone detection may occasionally be possible in exceptional circumstances, the sceptical reader should adopt a 'show me' approach to any such claims.

Surface patterns are often visible in the ground surface (with sufficient resolution, as in LiDAR bare-earth models) as depressions or mounds associated with graves, and these can also appear as concave signal patterns in GPR. We have also noted that when grave slumps are filled in with additional material (often sand or gravels), these can accentuate the surface pattern.

Most burials studied with GPR are rectangular with a long and short axis (approximately 1 × 2 m). When GPR lines are collected parallel to the short axis, the signal reflection between the vertical boundaries can create visible wave interference effects including a concentrated dome-like pattern above the upper boundary, which is similar to a hyperbolic 'tail' effect found with point targets. If the upper boundary is sufficiently reflective, this part of a grave can also generate hyperbolic tails on either side of the grave shaft discontinuity due to the above-mentioned elliptical footprint of GPR. This hyperbolic-like shape is frequently cited as a defining trait of burials in GPR (see Table 1), but it is also visible in subsurface volumes with proximal vertical walls such as a service line trench or archaeological excavation (Bigman, 2012). In our experience, this effect is not present across the long axis of a rectangular grave or when the angle of approach to the short axis is larger than 45°. As we note below, formal experimental testing of these parameters is necessary to define these effects.

Basin-shaped burials are underrepresented in the literature we reviewed, although they will likely be more common in informal and clandestine burials than in cemeteries. Conyers (2016, 41, 55) notes that this boundary shape can produce its own wave effect of an X-pattern within the basin, similar to what is visible in large (+25 cm) pipe voids scanned in cross section.

Figure 3 shows the frequency of the traits listed in Table 1 per citation. Only two traits are represented in more than 15% of the literature: stratigraphic discontinuities (54%) and hyperbolic effects at the upper boundary (32%). These results are likely skewed by the global sample, which combines results from many geological contexts. We suggest two qualities of the population from which this sample is drawn: (1) This list is likely not exhaustive, and more traits will be noted as more areas are studied, and (2) local conditions are unlikely to include the full suite of traits and instead include a subset. The former suggests that greater variability exists than we currently know, but the latter implies that specific scans will not have to contest with the full range of possible trait variation. There is a third potential effect at work here: Authors tend to report only the traits they rely on for positive identification rather than the full suite of traits they encountered from burials. These suggestions need to be tested against data, and we recommend the publication of local trait results and further regional and global overviews, perhaps focusing on specific kinds of geological contexts.

4 | ANALYSIS

In cemetery contexts, burials are frequently visible in plan-view visualizations (amplitude maps) as rectangular features representing the grave shaft (Schultz, 2012). Most applications of GPR in cemetery contexts rely on amplitude maps (i.e., the shape, size, location and orientation of a generalized area of high intensity reflections) and on two main GPR traits visible in radargrams (stratigraphic discontinuities and hyperbolic effects above the upper boundary of the high water level within the disturbed soil of the grave shaft). We argue that these principles are sound and cover most burials within formal cemeteries. As GPR is applied more frequently in less-formal contexts, burial identification will need to rely more on specific trait analysis to distinguish graves from other subsurface features of similar size, to identify graves in more heterogenous geological contexts and to identify graves that do not conform to standards of size and shape commonly found in cemeteries (i.e., child graves at IRS sites in Canada). From current research, we cannot yet determine if any GPR signal traits are unique identifiers of burials and thus only visible in graves; our literature review suggests not. We are unlikely to define a single suite of traits characteristic of only burials because graves have analogues in natural and anthropogenic subsurface patterns.

GPR interpretation currently relies almost entirely on visualized projections of reflected amplitude in two dimensions either vertically (radargrams) or horizontally (amplitude maps) when lines are collected in grids; grids can also be the basis of 3D volumetric visualizations, which is an emerging analytical trend (see, e.g., Büyüksaraç et al., 2014). Amplitude maps and 3D volumetric visualizations are projections of intensity from arrayed radargrams that are useful for identifications of potential targets based on size shape and orientation (Doolittle & Bellantoni, 2010; Larsson et al., 2015; Schneidhofer et al., 2017). Radargrams contain additional data (polarity, wave effects, point vs. planar patterns, etc.) and are typically the basis of target identification, especially in complex subsurface contexts (Downs et al., 2020, although Molina et al., 2015 report the opposite in an experimental context). It is possible, though not yet attempted to our knowledge, to work with the 3D cube of reflected numerical data from grids through direct statistical analysis rather than via visualizations. The traits listed in Table 1 are from radargrams, though many authors also use amplitude maps or (less frequently) volume models to locate and identify potential targets. It is also possible that the fast-emerging field of artificial intelligence (AI) may help with GPR-based interpretation of graves, provided that the AI can be trained with a sufficient number of unambiguous grave signatures and be coded with clear logical rules for evaluating data. Burials are composite features that may contain elements such as planes, points and voids. Considering each in turn allows us to unpack some of the traits listed in Table 1.

4.1 | Planar effects

Planar effects may be influenced by the shape and size of materials having dielectric contrasts, in part because of the effect of the angle of the EM signal. Reflection strength is greatest when the boundary is planar, and the angle of incidence nears 90°. For example, subsurface bedrock layers underlying unconsolidated soil/sediments are generally visible in radargrams as sharp boundaries of strong reflection in correlate well with their physical shape in the ground (Barone & Di Maggio, 2019). This is due not only to the strong dielectric contrasts in materials but also because reflections are generated most strongly when the GPR antennae are directly above (i.e., perpendicular to) the interface, minimizing downward transmission through refraction. The signal both changes direction at the threshold and reflects to the source depending on the angle of incidence and the permittivity difference between the two materials.

4.2 | Point effects

When the shape of the boundary is not planar, the GPR reflection patterns become more complex. Small shapes with large dielectric contrasts with respect to their surroundings (e.g., spherical stones in loose sediment or a metal cable or pipe approached at right angles to its length) create point sources for reflections: small targets that are highly reflective at any angle of incidence. These generate reflections beyond the 90° point of intersection (when the antennae are directly above) that generate hyperbolic shaped 'tails' on either side of the target; this is due to the point-source nature of the target, as well as to the elliptical 'footprint' of GPR energy referenced above. This hyperbolic reflection pattern does not correlate with the real shape of the target except near the apex of the hyperbola. This tail-like effect is a consequence of both the reflection at the refractive boundary and the curved interface which reflects the signal back to the device at any angle of approach, which is why such hyperbolas are commonly used to help estimate wave velocity in the migration steps of GPR processing software, mentioned below. Point targets are a common form of trait listed in Table 1 as grave contents. Cavalcanti et al.

(2018) report on experiments with pig cadavers in different burial formats and conclude that graves containing bodies are more visible than grave shafts with no burials. Specifically, the lower boundary effects were more visible, which the authors attribute to the higher water content from the burial itself mediating the loss of signal at burial depth.

4.3 | Combined effects in formal (i.e., rectangular/in cemeteries) graves

Rectangular grave shafts have six planar boundaries (four sides, top and bottom boundaries). The short vertical planes appear as vertical interfaces largely independent of each other because of their separation. The longer planes present a similar effect but with the addition of a concentrated reflective effect at the upper boundary resulting from repeated reflections between them. In some cases, this zone is sufficiently reflective to generate hyperbolic tails on either side of the grave similar to that of a highly reflective point target (Vaughan, 1986). These are the 'wave effect' and diffractive hyperbolic effects listed in Table 1. The upper boundary likely adds to these effects and generates its own planar discontinuity. This boundary is the upper margin of the water difference between the grave shaft and surrounding sediment, and so can vary in depth with changes in water table, rain and even in different moister regimes between nearby graves. The lower boundary is less mobile in GPR mapping and also acts as a planar boundary, frequently made more visible than elsewhere in the grave shaft by high water differences between the grave matrix and surrounding sediments. The lower boundary is also the site of the actual burial, and so can be amplified by point targets such as metal from coffin hardware and casket voids, as noted above. As listed in Table 1, several authors note the appearance of point target features that define grave contents, including major skeletal elements and the grave position (extended or flexed) and orientation. Nobes (1999) suggests that the head of a burial is visible as the area of greater reflection. To reach the depths of the lower burial shaft interface (~1–2 m), the typical frequencies used are too low to resolve the grave contents or interred individual with much clarity (King et al., 1993). As discussed above, there are substantial wavelength/resolution and dielectric-contrast reasons why direct detection of human bone should be highly uncommon in GPR studies, except in very unusual conditions. Metal coffins (see Conyers, 2013, p. 130, fig. 8-2) create very visible patterns, but these are rare forms of interment in the literature.

Several authors (Gaffney et al., 2015; Hansen et al., 2014) caution that even within cemeteries, additional taphonomic effects such as rodent burrowing can add complexity to radargrams, a process that is likely more frequent in less-formal contexts. Formal experimentation is uncommon and could represent an area of research with considerable value. Examples often focus on forensic studies in which recent burials are varied by clothing, burial form and so on and monitored over time. Schultz et al. (2016) are a significant example of this over long terms and of the exploration of exploring GPR collection parameters (see also Molina et al., 2016; Pringle et al., 2012, 2016). These latter two studies illustrate key experimental controls (including monitoring climate, depth of interment and empty grave shafts) and important results. The latter include decreasing signal strength with decomposition starting within a few years of burial, that shallower graves tend to produce stronger signals, and the potential value of lower frequencies (e.g., 250 vs. 500 MHz) to locate adult-sized graves against geological signals (Schultz et al., 2016). The increased availability of combined multichannel GPR arrays is likely a valuable improvement on single frequency units. Experimental forensic results provide us with both a valuable tool for methodological refinement and a key caution: The visibility of burials, especially clandestine burials, will vary in GPR results by many local conditions, and much work remains on defining these correlations. However, it must be emphasized that the strong dielectric contrast between cadaver tissue does diminish over time, with the other end-member being human bone, which normally has little dielectric contrast compared with common soil and sediment types. Therefore, the utility of cadaver-based studies to grave detection in older cemeteries is presumed to be somewhat limited.

4.4 | Time

If a grave is visible in GPR because of its different geological/soil properties, and if those properties transform over time to become more similar to surrounding sediment/soil (Koppenjan et al., 2003; Nobes, 1999; Schultz et al., 2016), then GPR may be expected to have a time limit on the identification of burials (Dick et al., 2017). Schultz et al. (2016) conclude that the GPR signal of clandestine burials begins degrading within months. However, this will be variable depending on factors such as preservation, burial practices and geologic/soil conditions. Our own experience indicates that graves in excess of 100 years old are fainter but often still visible (see also Conyers, 2013, p. 151, figs. 8–31). Barone et al. (2016) report on a potential grave identified in GPR from 1875, and Dick et al. (2017) find only a weak correlation between GPR traits and time since burial. Short-duration experimentation in which burial of known targets (commonly pig cadavers) are monitored over <10 years shows little change in reflective strength of signal (Booth & Pringle, 2016), but that seasonal variability had a more pronounced effect (Jervis & Pringle, 2014). Schultz et al. (2016) report from experimental results that GPR signal visibility increased with rainfall, a result also noted in van Shoor et al. (2017). Changing patterns of burial practice over time may also have a visible effect on GPR results (Doolittle & Bellantoni, 2010).

4.5 | Non-formal burial contexts

All of the examples and traits in Table 1 focus on rectangular grave shafts in relatively homogenous sediments of small particle size—the common parameters of burials in formal cemeteries. While some missing children from IRS landscapes are buried in such locations, some are also likely to exist in less-formal places. By 'formal', we mean that the selection of a location, the placement of graves and the curation of the history of use of the cemetery was standardized and public. Many such places are recognized with special land-use designations in legislation and protection in law. Some religious orders define cemeteries in spiritual terms, creating parallel systems of formality. For GPR analysis, the key traits often found in formal cemeteries are a low reflective context, an ordered arrangement of burials, rectangular grave shafts of similar size, the placement of makers such as headstones, patterns of surface contour shape associated with grave placement, a recording system of interments and oral knowledge of the history of the cemetery. The inverse of this (less formal) refers to places of burial where such standards are less apparent or missing (Akinsunmade et al., 2019). There are a range of these including organized places of burial that were never transitioned into the public register as cemeteries to clandestine places where burials were intentionally hidden. The absence of standards in planning and curation add variation to burial form in four main ways: grave shape, grave location, grave patterning and the qualities of the subsurface (Dick et al., 2017; Novo et al., 2010). Similar patterns can occur in archaeological (i.e., ancient) graves (Conyers, 2006; Gavin et al., 2014). Forte and Pipan (2008) illustrate the challenges of using GPR in areas of high topographical relief, such as burial mounds. Polymenakos (2019) discuss the challenges of using GPR to locate graves in a complex geological context.

The standard rectangular grave shaft is designed to accommodate a standard sized adult coffin. Burials of this shape also minimize labour and to allow for maximum use of cemetery area. Rectangular shafts are not the easiest shape to excavate, and anyone without a formal intent will be more likely to excavate a basin shape, a depression with curved walls and floor and an elliptical area. This reduces two key effects visible in GPR or rectangular grave shafts: the diffractive hyperbola that is consequential to the reflections of EM waves between the parallel vertical walls of the short axis and the well-defined planar transition at the bottom of the shaft. We lack clear empirical evidence in the literature for the response of a basin-shaped elliptical shaft, but we expect these traits to be absent or muted. A basin shape also presents less dramatic vertical difference in the boundary between the contents of the grave shaft and the surrounding sediments, also suggesting a stratigraphic discontinuity that is less defined in GPR by its margins and more by its central properties.

We have identified burials of different sizes in cemeteries including infants, children, adults and small boxes holding cremated remains. In most cases, these were located based on prior information to guide our search and confirm our results. Small-sized graves in informal contexts will be more difficult to locate because there are many natural subsurface features that have similar geophysical properties. The challenge ahead will be to define confidence of burial identification in such conditions. For example, we have identified burials in ancient shell-terrace village platforms. These are complex anthropogenic contexts that contain a range of burial-size features (pits, post molds, hearths, etc.) and ancient burials.

We employ an ordinal scale evaluation of uncertainty in our work, although we recognize the need for more quantitative rigour. Daniel (2015) proposed a Burial Confidence Index, a co-efficient of variation based on an inventory of core traits defined as silos (surface patterns/monuments, historical/archival data, GPR and arrangement and order). Each trait is given a specific weight towards the silo and the silos combined to form an index value between 0 (no grave) and 100 (certainty). In practice, neither extreme could be defined (see also Dalan et al., 2010), but a test sample of known burials scored +85% in the GPR silo, and this was used as a metric to identify unmarked graves for which no other data were available (other than presence in a cemetery). Such work informs our ordinal scale (Table 2), which can be framed as approximate intervals of 20%, although greater refinement of the correlations between GPR traits and known burials is necessary to improve this scale; it is possible that different geological contexts will benefit from their own locally constrained approach.

TABLE 2 A simplified grave identification schema and their characteristics.

Classification	Characteristics	Confidence of a burial
No evidence of a burial	• No signal in radargrams or amplitude maps.	Very low
Unlikely/ unknown	• No clear signal difference from background in radargrams or amplitude maps. • A visible pattern other than a burial.	Low
Possible grave	• A weak but visible signal in amplitude maps of approximately the appropriate size, shape and orientation as a burial. At least one clear dimensional trait in the amplitude map (shape, size, depth and orientation). • GPR traits appear in a minority of intersecting radargrams. • Contains *at least one* of the six types of burial traits listed in Table 1.	Moderate
Probable grave	• A clear visible signal of at least two traits in amplitude maps of the appropriate size, shape, depth and orientation as a burial. • GPR traits appear in a majority of intersecting radargrams. • Contains *more than one* of the six types of burial traits listed in Table 1 including evidence of a stratigraphic discontinuity.	High
Likely grave	• All of the probable grave characteristics are met. • Burial is identified in one other non-GPR data source.[a]	Very high

[a]This does *not* represent the entire GPR interpretive process but provides a short explanation of the classifications used. Additional, non-GPR information can itself be conclusive of an unmarked grave; alternately, such evidence could increase the confidence of a burial by one tier in the table.

- No evidence of a burial: no evidence of an anomalous reflective target of any kind. We cannot conclude that no burial exists, but we can note that there is no GPR evidence for one.
- Unlikely: GPR reflection signals but diffuse and not characteristic of shape or traits of a burial. More experimental work and a larger inventory of know examples will refine when a burial is not seen in a GPR signal. This category also includes GPR signals for identifiable non-burial features such as service tranches or animal burrows.
- Possible: some elements of a burial pattern in GPR but not all; typically, this includes a visible—though weak—pattern of stratigraphic discontinuity of appropriate size or some subset of burial traits from Table 1 but inconsistently visible in the intersecting radargrams. We argue that one trait in amplitude maps (size, shape, etc.) and one in radargrams defines this category.
- Probable: a clear pattern of the major traits associated with burials (which varies) including a volume of stratigraphic discontinuity and associated traits (which in rectangular graves) includes wave effects such as shouldering, a concentration of signal at the upper boundary with diffractive hyperbolic tails and a clearly defined lower boundary with point targets. This category captures the typical confidence of a burial in GPR in cemetery contexts.
- Likely: a probable grave in GPR with an additional non-GPR line of evidence such as a different geophysical data set, archival or survivor evidence. Appearance of a signal within a known cemetery (formal or informal) constitutes a second line of confirmatory evidence.

The thresholds between these divisions and even the definition of each level are preliminary. However, this scale corresponds to the logic found in the sources of Table 1 and with our own experience. In practical terms, the most importion division for communities is binary: Is there evidence of a burial or not? However, a five-stage ordinal scale allows us to better anticipate a more quantified approach to uncertainty that remains a goal.

5 | CONCLUSIONS

The challenge ahead for the application of GPR to assisting in the location of burials outside of cemetery context, including those associated with IRS landscapes is considerable but not insurmountable. We propose four avenues of research that can advance the identification of burials beyond formal contexts using GPR: more sampling, simulations (Akinsunmade et al., 2019; Hammon et al., 2000; Molina et al., 2015), experimentation (Almeida et al., 2016; Pringle et al., 2008; Salsarola et al., 2015; Schultz et al., 2016; van Shoor et al., 2017) and new approaches to statistical evaluation (Mazurkiewicz et al., 2016), such as modelling the boundaries of signal coherence (Trinks & Hinterleitner, 2020). Each contributes to the larger effort of refining the method and will assist in the specific tasks associated with IRS landscapes.

The basic relationship outlined here is between a heterogenous population, of all possible burial types in all possible contexts, and a non-representative sample biased towards cemetery contexts. Additional examples of GPR results that expand the sample will assist in refining the method. The rigorous inventorying of sedimentological conditions and specific traits associated with burials from local studies is a key facet of this work. Expansion of Table 1 with additional traits, a range of geological contexts and, more importantly, quantitative results of trait frequency associated with burials will add considerably to our understanding of variation in this work.

Many GPR analytical software platforms permit simulations. Expected types of burial forms in different geological conditions can be simulated to generate trait patterns that can aid in the interpretation of actual radargrams. Simulations can also assist with interpretation of complex patterns where signals of burials are mixed with geological patterns. Simulations create an independent list of traits that both clarify and be assessed against field results, while providing a control over a wide range of parameters and conditions.

The method would also benefit from formal experimentation in two directions. First, parameter testing conducted against known burials can assist in developing general practices for best results. GPR settings are largely based on industrial applications and would benefit from evaluation and, as modification as warranted. Second, field testing with artificial burials of different forms in different geological contexts would improve the representation of experimental results.

Lastly, the GPR interpretation of burials in our survey of published results is exclusively based on the judgemental interpretation of patterns in data visualizations. In this paper, we have argued, following Daniel (2015) and Martin and Everett (2023), for the benefits of a more explicit approach to trait identification that can be summed towards a burial identification. Doing so permits two areas of statistical strength. First, traits as components of burials can be identified and evaluated for their strength of correlation, both in general and, more usefully, in specific conditions. A range of evaluations of correlation, and thus predictions of association, are possible. This can be imagined as either conventional statistical tests or as demonstrated by Cornett and Emenwein (2020) as examples of machine learning. The standardization of GPR visualizations, especially radargrams, likely lends itself to computer-assisted identification. GPR interpretation is entirely conducted on visualizations: projections of numerical data as patterns of shades of colour. Behind these is a numerical pattern of reflected signal amplitude. In grids, this is a 3D cube of values which could be directly assessed with statistics. Patterns in numbers would mirror visualizations, but statistical assessment of the direct values would permit mathematical assessments of uncertainty.

The challenge of interpretation in the application of GPR to the search for burials distils to our assessment of uncertainty. Cemeteries present excellent contexts for GPR resolution of grave-like reflections; add to this the additional lines of independent evidence often available, and the resolution of uncertainty is easily overlooked and unnecessary to define. Any grave-sized feature in the expected position and location is likely a burial. However, when these conditions vary, as they are likely to do when we explore less-formal contexts such as landscapes associated with IRSs in Canada, certainty of interpretation becomes more difficult, and, thus, the utility of creative interpretation pathways increases. Such paths should be explicit and based on methods testing, hypothetical or simulated evidence and the descriptions of correlated traits as elements of GPR results. Ideally, such correlations can be quantified allowing for a more statistically robust evaluation of uncertainty. Such approaches benefit any GPR analysis in archaeology; they are especially important when addressing the complex and urgent needs of missing children from residential schools.

CONFLICT OF INTEREST STATEMENT

The authors declare there are no conflicts of interest regarding this research.

DATA AVAILABILITY STATEMENT

Access to the reviewed materials discussed in this article is available online through publisher databases.

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