CASE REPORT

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Location and Assessment of an Historic (150–160 Years Old) Mass Grave Using Geographic and Ground Penetrating Radar Investigation, NW Ireland*

ABSTRACT: Reburial of human remains and concerns regarding pathogens and pollution prompted the search for, and assessment of, a 156-year-old graveyard. To locate this graveyard, historic and anecdotal information was compared to landscape interpretation from aerial photography. To assess and map the contents, surface collapses, metal detector indications, and ground-penetrating radar (GPR) were used. Some 170 anomalies compatible with burials were identified on 200 MHz GPR data, 84 of which coincided with surface collapses, suggesting both noncollapsed ground, subsequent infill, and multiple inhumations. The graveyard was possibly split into Roman Catholic plots with multiple inhumations; Protestant plots; and a kileen, or graveyard for the unbaptized (often children). The work serves as one approach to the location and mapping of recent and historic unmarked graves.

KEYWORDS: forensic science, aerial photography, ground-penetrating radar, mass graves, geomorphology, metal detector

Mass graves contain multiple, usually unidentified human corpses: there being no definition as to the minimum number of bodies interred (1). Clandestine burials likewise may contain one or more unidentified bodies. Both clandestine and mass graves, as well as buried victims of mass disaster (landslides, tsunami) can be recent (Middle East, Bosnia/former Yugoslavia, Cambodia, Asian Tsunami Boxing Day 2004, Gujarat [India]) or historic (World War II/Holocaust, Tulsa Race Riots, Spanish Flu/Plague/Black Death). Scientific investigations into such burials can be disjointed, tending to concentrate on first locating, second mapping or assessing the site, and third victim recovery/identification, yet the correct identification and assessment of mass graves is a matter of international concern (1), suggesting an integrated method of study is desirable. Few studies have been made where these three aspects are brought together: understandably as remote sensing, geophysics, archaeology, and anthropology all have their separate roles to play in the process of burial location, cadaver exhumation, and victimology (2,3). In this study, an historic graveyard has been located from geological and geographical interpretation of aerial photography. On-site visits have confirmed the location, and allowed assessment of the number, depth of burial, and possible religion/age (of victim) by survey and geophysical measurement.

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The Problem

Expansion and redevelopment of redundant plots of land in both brownfield (former urban land) and rural locations may result in the accidental discovery of buried materials. These may be "good" (historical or archaeological remains, mineral or water resources) or "bad" (contaminated land, human or animal burials). With inhumations, length of time in the ground, the number of victims, and the type of burial/ground conditions all need to be determined for any criminal enquiry, assessment of environmental hazard, and possible repatriation, reburial, and remediation of the site. Major considerations are what pathogens are present in the burials: some pathogens (e.g., smallpox) can survive for hundreds of years, depending on oxygen availability, rate of decay, and hydrological conditions. Just such a scenario forms the basis for the current work. The Irish Potato, Irish, or Great Famine (*c.* 1845–1851) caused the deaths of over 1 million people and the emigration of another 2 million (4). The death of over one-eighth of a country's entire population makes this proportionally more destructive than any famine of modern times. The famine began as a natural catastrophe (destruction of successive potato harvests by the fungus *Phytophthora infestans*), but its effects were worsened by the ruling British government, creating extreme bad feeling and mistrust that lasts to the present-day. Many include the injustices of the famine as being instrumental in the civil war (1919–1921), partition, and thence the troubles of 1969–1998.

Many of the afflicted were of rural descent (the cause being a crop failure), with few means of support, material goods, or money (4). Many such paupers travelled from their homes, often with children, to find themselves eventually thrown on the mercy of the welfare institutions, including workhouses and hospitals for the poor where the high mortality rate resulted in what was sometimes mass burial (multiple inhumation). Many victims were either

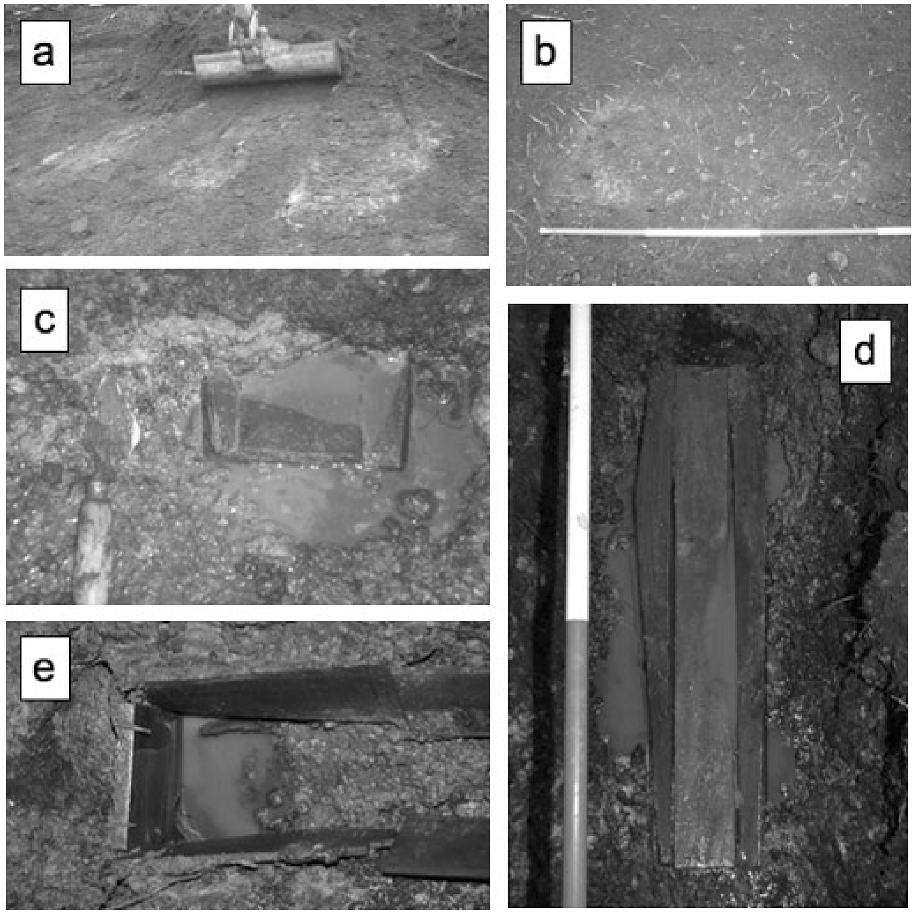

FIG. 1—*Sequential photographs of the first site to be discovered and excavated (hospital grounds). (a) Backhoe exposing three light patches above burials. (b) Excavated light patch. Pole is 1.6 m long (each section is 50 cm). (c) Initial exposure of the foot end of a small coffin. Trowel is 2 cm long. (d) Excavated coffin,* c. *1 m long. (e) Opened coffin, showing a child's skull, same dimensions as (c).*

wrapped in a shroud and buried, or placed in crude coffins (4). Clothes of any value were removed, although this was rare, the unfortunate sufferers in most cases having given up anything of value. Hence there now exist mass graveyards with mixed coffin or no-coffin inhumations of 150–60 years age, with no headstones and little other visible indication of the number or timing of the burials (authors' personal observations).

The expansion of a hospital in the northwest of Ireland in 2004 caused land to be redeveloped. During removal of topsoil, site-workers noted light patches in otherwise dark soil (Fig. 1*a*) and an archaeological assessment was undertaken. This confirmed the shallow (sub-topsoil, at 5–10 cm) lighter patches (Fig. 1*b*). Site work was halted at this point, whilst an archaeological excavation was planned. In addition, historic plans of the site were consulted, in order to find out why the predicted burials had not been anticipated. These records showed the site to be the forerunner (1845) of a later (1849–1851), larger site. Both were thought to be pauper graveyards. The deceased may have died of any number of diseases, including smallpox. Thus during excavation, full personal protection was deployed. Victims buried in shrouds were anticipated, yet five crude wooden coffins (Fig. 1*c,d*) were found, with good to reasonable preservation of human remains inside (Fig. 1*e*). The recovered human remains were reinterred at a local Christian churchyard and the site redeveloped as planned. Concern was raised that historic records showed this to be a forerunner of a larger site, the location of which was unknown. This had two implications: the political problem of many pauper graves going unmarked, with fourth generation relatives still alive, and the environmental health concerns of many diseased burials in uncontrolled circumstances. This could have repercussions for local water quality, as well as future developments in the area. First, the site had to be correctly located. Second, the number/and nature of the burials had to be assessed. This exploration and assessment process reflects the first two stages taken when locating individual and multiple unmarked (e.g., clandestine) burials, with excavation and identification (anthropology) being the next stage prior to repatriation of human remains.

Searching for the Graveyard

Historic records recovered from the Public Records Office (Belfast) during assessment of the first site were vague in their description of the second site, except giving a general location (what are termed townlands in Ireland) and a description of a rectangular site capable of holding some tens of burials. This latter statement was not helpful, as depth of burial was not given and the possibility of multiple inhumations exists. The townland indicated is in the west of Northern Ireland. The deep geology comprises Carboniferous (Pennsylvanian in N. America) siltstones and sandstones, with up to 20 m of glacial till, postglacial fluvial-lacustrine silts and sands overlying bedrock. The region comprises agricultural land with a gentle regional slope to the south with no topography over 4–5 m. Small ditches dissect the landscape, and borehole/waterwell records (held at the Geological Survey of Northern Ireland) indicate a water table at 2–3.5 m. Historic maps of the area indicate a graveyard after the townland name, but with no locational details. Modern maps show no evidence of a graveyard. Such lack of detail concerning pauper burials is not uncommon, as they may not be in consecrated ground, often with no church or chapel associated, and more commonly near workhouses, hospitals, or prisons that have subsequently been redeveloped. This lack of information mimics what occurs with many graves and mass burials associated with wartime and genocide. If such sites need to be found, aerial photography and remote sensing are often used to prioritize targets and reduce costly ground surveys (2,3). More modern burials (nominally, less than tens of years) have both a thermal signature and a strong influence on vegetation (2,3), making remotely sensed information (infra-red, ultra-violet, multispectral imaging) useful in target location. In older burial sites (nominally, tens to hundreds of years), thermal signatures and effects on overlying vegetation will be suppressed and techniques such as those deployed in this study likely to be more effective.

Aerial Photography

Historic aerial photography from Royal Air Force overflights in the 1950s is held by the Ordnance Survey of N. Ireland and University of Cambridge repository. These allowed definition of a likely area, centered on the named townland (historic records) that was rephotographed from a lightplane, flying at 300 m elevation. The resultant image (Fig. 2*a*) is of good definition, allowing rectangular sites and access roads, as well as any likely associated buildings to be outlined (Fig. 2*b*). Over-reliance on finding existing rectangular sites was avoided, this being subject to possibly inaccurate historic records, or to redevelopment/ploughing/hedge removal that would have reduced the graveyard's "footprint" on the landscape. Thus linear features (existing or buried), access roads, and suitable sites were all marked on the aerial photograph (Fig. 2*b*) and then assessed. Target Area 1 was found to be surrounded by mature trees, of a suitable post-famine age. Farm buildings have subsequently been built in the middle of the site, making it likely that during foundation excavation, burials would have been found. However, they may not have been reported. No older (1800s) buildings are known near this location. Target Areas 2 and 3 were both of similar nature, being small and subsequently allowed to largely overgrow, with some small farm buildings associated. Burials here could remain intact although this location has no other historic buildings nearby. Target Area 4 is a larger version of areas 2 and 3, with records of a small workhouse to the north, making it a good candidate. Again we stress an avoidance of possibly inaccurate records. Old roadways were observed near this location (Fig. 2*b*).

Site Surveys

The four target locations were visited on foot. The whole area could have been surveyed on foot, requiring time, effort, and access permission. A comprehensive walk-over terrestrial survey would have to demonstrate adequate coverage, and yet the dimensions of the graveyard were not known. This would have to have been guessed at and survey transects walked that were smaller in spacing than the smallest potential width of the graveyard, in order to ensure the target was crossed. By using aerial photography, target locations could be visited quickly and ultimately a larger area surveyed quickly. Target Area 1 is the most elevated of the targets (30 m above OD), being at the eastern side of a rounded hill (extends to the north-east of the photograph on Fig. 2*b*). The site survey as well as discussion with the local farmer determined that

FIG. 2—*Raw and interpreted aerial photograph of the area historical records indicated a pauper's graveyard to be located.*

glacial till (clay with cobbles) up to 3 m thick overlay sandstone bedrock in this location, with no sands and silts, as noted elsewhere. Foundation excavation for the modern farm buildings (chicken housing) had required a professional archaeological survey that had mapped and recovered material associated with Neolithic inhabitation at this site. Thus the chances of an extensive pauper's graveyard existing here were slim. Target Area 4 was visited next (it being next closest to area 1), where the evidence of a graveyard became so immediately apparent, areas 2 and 3 were only visited in order to complete the procedure. Had the graveyard been in either area 2 or 3 then the survey would have encountered some difficulty, as these sites had numerous small buildings, gardens, and trees, although it is possible that these sites had evolved like this precisely because they *did not* have graves in them.

Target Area 4 Survey

Target Area 4 is an elongate *c.* 100 m by 50–80 m northwest–southeast oriented site with access via a lane from farm buildings to the northwest and a lane to the southeast (Fig. 2*a*). The farm buildings are on the site of a former workhouse, and interviews with local residents indicated that a mortuary stood at the northern end of the site, which was locally referred to as a graveyard. The current owner provided one critical piece of information: that because of collapsing ground, the area has been periodically covered with imported, loose material, including a covering of up to around 50 cm of silt placed on it during the Second World War (1939–1945), during nearby construction works for an airfield. The farmer also filled in periodic collapses as he cut grass from the plot for hay and grazed some animals there. No indication of the age of the interred bodies was known. The site has a slope of around 1 m elevation from northwest to southeast (Fig. 3). Vegetation within the site comprises small bushes (Fig. 1*a*), grass (grazed by sheep and a goat) with daffodil and bluebells in hollows (Fig. 1*a,b*). Numerous elongate hollows, usually about 1 m long by 50 cm wide were noted, often with the long leaves of the daffodil bulbs (underground roots) protruding to where they had been cut or eaten by sheep/goats. Depressions (variable size, between 10 and 30 cm deep, 30 cm to 1 m wide/long) without daffodil bulbs were best observed at low light (dawn or dusk: Fig. 3*c*), when they became so obvious as grave-shaped hollows, they could be marked with environmentally friendly blue chalk spray (Fig. 3*d,e*). The only concern that these were not graves was some curious shapes in the ground conditions ("L"-shaped depressions [Fig. 3*f*], linear features) and the large number of depressions (Fig. 4). Each surface depression was surveyed using a total station and some 84 depressions noted. Historic records had indicated that this contained more victims than the initial hospital site, which we took to mean may be 10 or 20 further victims, with more in local graveyards. Concern that a major burial site of diseased victims existed on a local aquifer (postglacial sands and silts), with a deeper regional sandstone aquifer beneath resulted in the survey being halted and the site reconsidered. A more complete topographic survey of ground conditions was made, indicating breaks of slope, and integrated with the total-station positions of each depression (Fig. 5). Discussions with archaeologists revealed the possibility that our depressions were the likely location of multiple inhumations, with other, single-occupancy graves existing elsewhere in the graveyard or even beyond its limits. These may not have a surface expression, on account of being too deep, or the covering of silt had obscured any collapse. The other concern was to ascertain the geometry of the underlying sand and silt aquifer. Thus a geophysical survey, to comment on both number of burials and geological conditions was commissioned. Geophysical literature current at the time indicated that ground-penetrating radar (GPR) could provide some indication of both grave depth and occupancy, as well as information on the surrounding surficial geology. As the initial results of the survey had raised media awareness and made the local inhabitants somewhat concerned, the survey had to be as comprehensive and rapid as possible, so a metal detector was also deployed, in order to help assist in assessing grave contents (most paupers being buried with no worldly goods). In ideal conditions, a magnetometer survey and electromagnetic survey (using a device such as the EM38) would have been completed. We used a White's 750 dual-loop metal detector in normal "sweeping" mode, with indications marked on the ground and surveying using a total station.

GPR

Use of GPR in Burial Location

GPR has become one of the main geophysical tools for those involved in the search for buried organic remains: thus we summarize the theory behind GPR data acquisition and the workings of GPR systems (below). In addition, the reader will find such descriptions in most of the works cited below. Prior to 1992, GPR was used by law enforcement search teams and the military throughout the world but was rarely documented, except in general terms in newspaper articles. Reynolds (5) explains how the method works, and gives uncited information on the use by the US army when locating Viet Cong tunnels in the Vietnam War. One the first discussions on the uses and abuses of GPR in locating gravesites was made by Bevan (6); Strongman (7) published a series of case studies from controlled environment burials, using 5-year-old bear carcasses as well as actual crime scene surveys. Owlsey (8) evaluated GPR against other geophysical devices and concluded that a physical probe was still a better device for use in the detection of soft ground around individual inhumations and buried objects. Miller (9) followed the Strongman (7) approach, with an evaluation of test sites against actual case studies. Miller (9) provides a review of work undertaken up to 1996, including using GPR to find Viet Cong tunnels in Vietnam, utility lines, landfill debris, areas contaminated with fluid pollutants, and plastic explosives. With regard to burials, Miller recounts how archaeological mapping of Japanese burial mounds, the interior of an Egyptian pyramid, and mud-walled dwellings in South America set the scene for forensic work in the search for graves. The application of GPR technology was at an impasse until 1996, as new technology and small, ruggedized laptop computers and data loggers were developed. A rush of papers in 2000 reflects these advances and their application to actual forensic cases (10) and, critically for this work, historic mass burials (11). The development of other geophysical techniques such as resistivity and magnetometry has caused a re-evaluation of GPR in comparison with other devices (12). Many of the early problems with GPR have now been solved: the development of shielded radar antennae has made usage in urban environments possible. The range of antennae available (25 MHz to over 2000 MHz [2 GHz]) now allows investigation of large subsurface features such as walls, foundations, moats, channels, and mass graves to small (centimeter-scale) objects and features such as plastic landmines, cracks in walls and pavements, or even the neonate inhumations. Wet, clay-rich and wet, salt-impregnated ground still cause difficulty in obtaining images of the subsurface where the large-scale disturbances of nature need to be separated from those made by humans. In problematic burial locations, extensive postacquisition

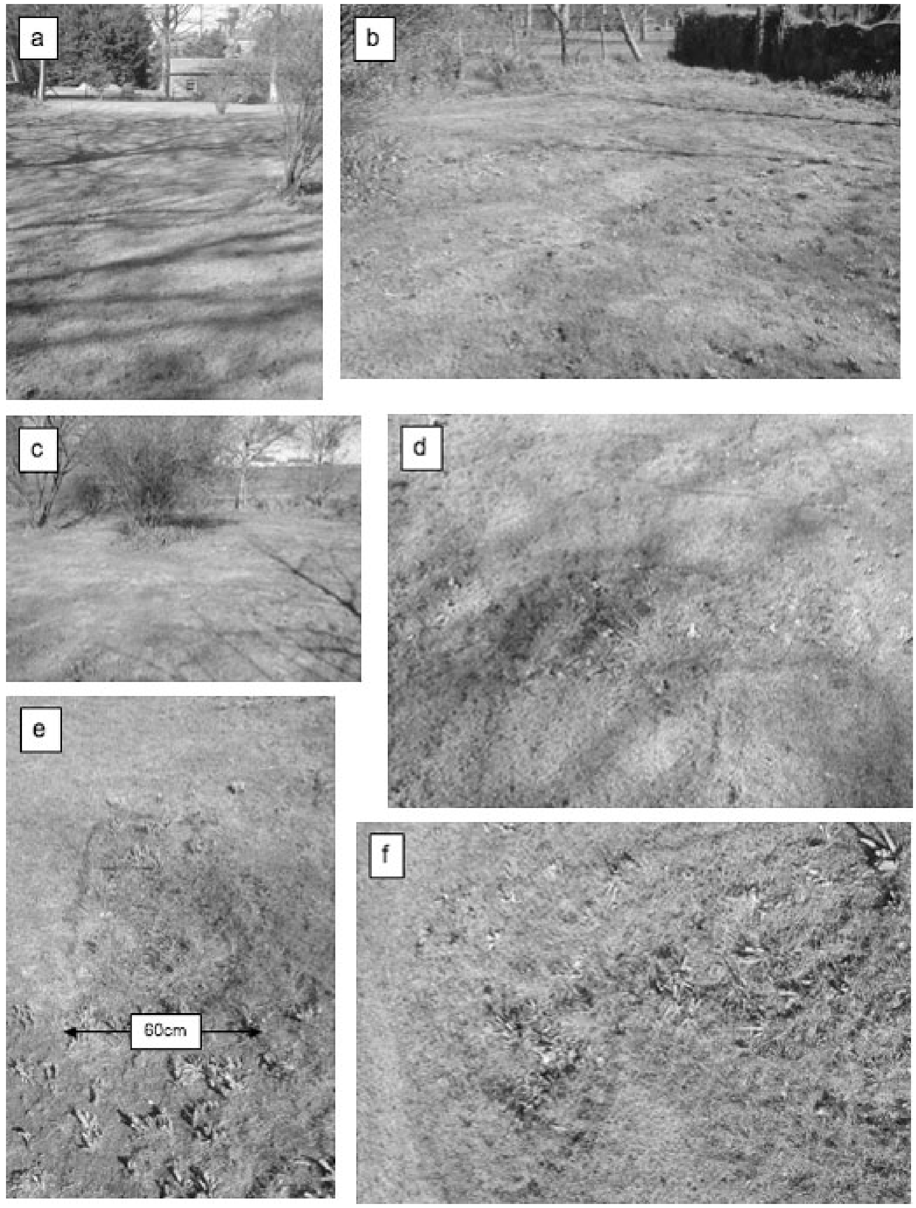

FIG. 3—*Target Area 4 (see Fig. 2) on an initial visit and survey. (a) View to the north, showing small bushes that caused some ground-penetrating radar (GPR) lines to be shifted: no interference from such bushes was noted on GPR data. (b) View to the northeast: the break of slope interpreted to be a buried wall or hedgeline runs from bottom right to mid-left of the photo. Some rectangular depressions can be seen. (c) View to the east, showing small bushes and patches of daffodil bulbs (underground roots with leaves protruding above ground). (d) Typical depressions, outlined in blue chalk spray. The lower depression has the typical growth of bulbs; the upper has a cross in a circle where a metal detector indication was noted. Each depression is* c. *1.5 m long. (e) Typical, bulb-filled elongate depression. (f) An L-shaped depression (see text for discussion).*

processing, other geophysical methods (13,14), penetrative investigative techniques, cadaver dogs, and geochemical sampling are required. For initial, noninvasive subsurface searching, GPR exemplifies the problems faced by all users of geophysics, that of controlled experiments, ground-truthing, and data. Published studies have continued and advanced (through time-series monitoring) the work of Strongman (7) in using pig cadavers for proxy material (15): these studies provide us excellent proxy information on the GPR response from buried cadavers. A common problem with both is the difference in geology, soils, vegetation, groundwater, and human influence between test-sites and the real scenes. Graveyards overcome some of these deficiencies but then create others. Coffins and deep burial are common in legal burials (2,3,16) yet very rare in covert murders or mass graves. Hence some practitioners have used places of rapid legal burial (flu epidemics, pauper graves) sites in preference to regular graveyards (11) in order to better understand the geophysical responses from coffin and non-coffin burials, whether individual graves, multiple burials, or mass graves (commingled remains).

How It Works

GPR uses the transmission and reflection of radio waves (typically 25 to 2 GHz) in much the same way as reflection seismic profiling uses seismic waves. Radar waves, introduced in the ground, may reflect back to surface when they intersect objects or surfaces of varying dielectric permittivity. Thus a GPR system requires a source antenna and receiving antenna (built to measure

FIG. 4—*Target Area 4 following a survey of all surface depressions and metal detector indications.*

the same frequency). The transmitting antenna generates a pulse of radiowaves that the receiver detects at a set time interval: the longer the time interval, (potentially) the deeper the waves will have travelled into the ground and back again. As the antennae pass over isolated objects (boulders, pipes, cadavers), they may generate hyperbolae, or arc-like reflections. Radar waves also travel horizontally from the transmitting antenna, which in open ground simply dissipate with distance. However, in areas with upstanding structures, especially those that have a significant dielectric contrast to their surroundings, interference from such surface objects can create artefacts on the radargram. When such isolated objects (metal poles, trees) are passed during a traverse, a series of hyperbolae may be generated that appear like a subsurface object but are simply out-of-plane reflections. Radar antennae are commonly elongate, generating radar waves in a widening arc from their long axis. Thus when moved in parallel to the antennae axis, the radar waves may reflect from a larger subsurface area (the so-called footprint) than when moved with the antennae at right angles to survey direction. Unlike other forms of electromagnetic radiation used in geophysics, radio waves have far higher rates of attenuation, and thus penetration and reflection depths are low. The receiving antenna has either electronic or fiber-optic link to a recorder that converts incoming radiowaves to digital format and displays these graphically as wavelets. As the transmitter–receiver array is moved, so these wavelets are stacked horizontally to produce a grayscale or color-intensity radargram. Parallel radargrams can be amalgamated to produce 3-D images or time-slice maps of successive subsurface layers. The speed of radiowave propagation is determined by the makeup of the transmitting medium: in this case the speed of light and dielectric permittivity. Magnetic properties can also influence radar wave speed. Changes in dielectric permittivity can cause radar wave reflection, without which GPR profiling would be impossible. Radarwave attenuation, or signal loss is extreme in conductive media such as seawater, clays (especially hydrous), and some leachate. GPR has good depth penetration (tens to hundreds of meters) in ice (with minor fracturing/interstitial water), hard rocks, and clay-poor quartz silts or sands. Vertical resolution *vs.* depth penetration is of major concern when choosing antenna frequency. Low frequencies (15–50 MHz) achieve deep penetration with poor vertical resolution in the received signal, due to the long wavelength. High frequencies (500–1000 MHz) show high resolution with weak penetration (centimeters to meters). Low-frequency antennae are large (a few meters long), high frequency antenna are small (tens of centimeters). Again, this can influence the use of the method, as deeply buried targets in enclosed spaces are virtually impossible to survey.

As with all geophysical methods, some intelligence concerning the likely size and makeup of the target is useful: where unknown or questioned, then a range of antennae should be used, and in very poorly understood locations, with other geophysical and invasive techniques. Moisture contents influence radar wave velocity because in homogenous media porosity has a direct relationship to dielectric permittivity. Thus dry sand will allow increased wave propagation: sand with high freshwater content will give improved vertical resolution. A major problem with unshielded antennae is the effect of out-of-plane reflections. It is easy to think of the radar wave as a focused beam (the ray-path at right-angles to the wave) when in fact the radar wave as it travels into the subsurface is more like a bubble, elongate-hemispherical at first, expanding and becoming distorted as it travels at different speeds into the ground. Thus lateral to the antennae, on or in the ground surface may be structures (trees, posts, drains) that cause reflections at ground level. The effect of these surface features can be diminished by altering the orientation of the antennae, or by shielding the above-ground portion of the antennae, such that the radio wave is directed away from the object, or only allowed to penetrate the ground. GPR has found its best uses in imaging glaciers, frozen ground, sand deposits (river deposits, nonsaline coastal sands), aquifers (porous nature), archaeological features (moats, buried buildings), and concrete/pavements.

Ground-Penetrating Radar: Data Acquisition

Data were collected in a dry weather period of March–April 2007 using a MALA RAMAC GPR system fitted with 100, 200, and 400 MHz unshielded antennae. Shielding of antennae should be considered in environments where adjacent structures (out of plane objects) can create anomalies on GPR profiles. The site of Target Area 4 (see below) comprises a generally open field with bushes,

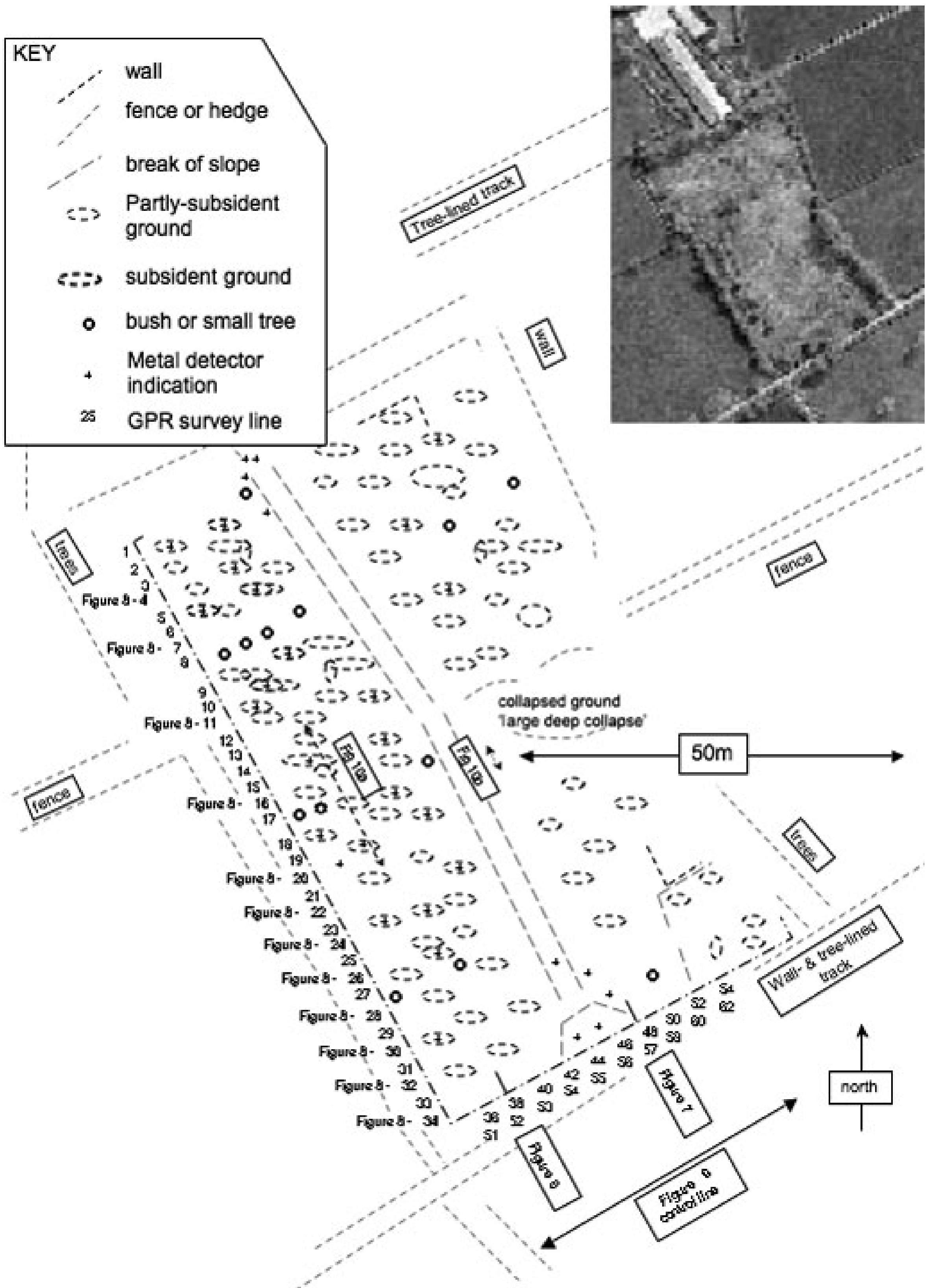

FIG. 5—*Target Area 4 showing the mapped surface depressions (see Figs. 3 and 4), metal detector indications, physical features, breaks of slope (a few cm in height), and the GPR survey lines, which relate to raw data and to subsequent figures.*

surrounded by some stone walls, some iron fencing, and large trees. Within the site, isolated bushes occur. Test profiles run adjacent to these structures showed no anomalous reflections that were obviously attributed to a known feature, thus shielded antennae were not required. The 100 and 200 MHz frequencies were generated on a step-size of 5 cm with fifteen readings per step: antennae were deployed both broadside—parallel and endfire to acquisition direction: 30 m survey lines took 10–15 min each to gather. 400 MHz data, acquired over individual targets (subsident patches), used a 1 cm stepsize: 10 m survey lines took around 10 min to gather. Surveys were focused in the graveplot and control lines were gathered in the ground surrounding the site (Fig. 5). Within the site, GPR transects were positioned 2 m apart, which with a "footprint" of *c.* 1 m diameter at 1 m depth (200 MHz data), should result in objects of 1 m length being imaged. Line spacings of 20 cm and 50 cm were used when 400 MHz data were gathered over collapse features. Data was viewed in the field on the Mala XVII viewer with gain applied. Data quality was good and the only extra processing comprised further application of gain (automatic gain control) and trace averaging (to "smooth" the profile) using Mala's Groundvision geophysical data processing programme.

The aims of the GPR survey were to determine possible multiple inhumations, locate burials with no surface depression, and to assess the geology of the site, with especial regard to possible aquifer conditions under any burials and thus leachate sources. Using the literature sources (above), our own experience of the often clay-rich ground of Ireland, and equipment availability, we chose 100 and 200 MHz antennae to survey the whole area and 400 MHz for investigating individual areas of possible burial. The next consideration was whether to use 100 or 200 MHz antennae, and what processing would be required in order to maximize data use and definition of any burials. We gathered 10 GPR profiles along the length of the Target Area 4 site (Fig. 5) in order to assess this. Figure 6*a* shows a comparison between raw (unprocessed) 100 and 200 MHz data, which shows convincingly that 200 MHz should be favored. Figure 6*b* shows the same profiles in which gain has been applied. This processing function should make deeper and subtle reflections more obvious, as well as limiting noise at shallower levels. The process actually decreased the resolution of the potential graves observed on both frequencies. In order to make sure these results were not due to some odd effect along lines 38 and 52, the same processes were undertaken in another side to the site (Fig. 7*a,b*, location on Fig. 5), with the same indications of how best to conduct the survey. Thus a 200 MHz grid was established and run according to the above acquisition parameters.

100 and 200 MHz Ground-Penetrating Radar: Results

100 MHz Data

Processed and unprocessed 100 MHz data from the "long" GPR lines (Figs. 6 and 7) show a prominent undulating reflector at 75 cm −1 m depth (labeled P on Figs. 6 and 7), with more flat-lying reflectors "infilling" these undulations above. A collapse in this reflector is noted on Line 52 (Fig. 6*a*). 1–2 m beneath this reflector (interpreted below as the original graveyard surface), the numerous small hyperbolae (arrowed on Figs. 6 and 7) common to many of the profiles may be observed. These hyperbole are associated with some "ringing" (labeled B on Fig. 6*a* and arrowed on all subsequent figures) in the data to 4–5 m depth (below ground surface). Beneath this, strong reflections are not seen, although undulating stratigraphy can be observed on both raw and processed data. A collapse (see Fig. 7*a* for an idea of its shape and depth) below the prominent reflector P is noted on Line 57 (Fig. 7*a*).

200 MHz Data

The strong reflector at just under 1 m depth seen on 100 MHz profiles is better-defined on 200 MHz data (labeled A on Fig. 7*a*). The numerous small hyperbolae of the 100 MHz data are also clearly seen. These may be of the "ringing" type, seen on 100 MHz data (labeled B on Fig. 6, for reference to all subsequent figures) or of an upper case A shape (a hyperbola with a flat reflection or bright spot below, labeled A on Fig. 6*a,b*). Some isolated, elongate reflections between 2 and 4 m depth (labeled E on Fig. 6*a*, for reference to all subsequent figures).

Ground-Penetrating Radar: Discussion

100 and 200 MHz Data

Reflector P most likely corresponds to an older surface in the area, most likely the original surface of the graveyard, prior to abandonment (post 1851), possible revegetation, grazing and covering with silt in World War II, with further grazing and vegetation growth since. Hence some of the anomalies suggested to be burials at 2 m depth or over, were more likely buried at 1 m depth; correspondingly, some anomalies at a current depth of 1 m may at times have been only just under the ground surface. This may help explain why material was laid on the ground here after 1851, and especially the layer of silt, in order to cover any exposed coffins or remains without having to exhume and rebury. The large shallow collapse (Fig. 6*a*) has no surface expression and may be an example of where material has been laid on top to level the ground. A similar collapse is noted along the line of an interpreted NW–SE oriented wall (Fig. 8), and it is possible a wall or removed hedge ran NE–SW across Lines 38/52 (Fig. 6*a*). Collapsed ground (noted during topographic surveys, see Fig. 5) is coincident with the "large deep collapse" on 100 MHz data (Fig. 7*a,b*). This collapse has a surface and shallow (Line 16 200 MHz data: Fig. 8) expression but appears to have a deep origin (Line 57 100 MHz data: Fig. 7*a*). The surface and shallow expression gave cause for concern that this could be a burial pit, more akin to the mass burials of modern genocides: it's deeper expression on 100 MHz data (Line 57: Fig. 7) suggests this has a geological origin. Nonetheless, this area would require careful excavation, incase of multiple burials, or weak substrata that could cause vehicles or people to become trapped in soft soil. Line 48 (Fig. 7*b*) shows a grey zone, lacking bright reflections, from 1 to 2 m. A vague, subhorizontal reflection, seen running through other, dipping surfaces, can be seen on other 200 MHz profiles (lines 20, 24, 26 of Fig. 8). The change in GPR texture above and below this suggests it may not be an air-wave or ground-wave multiple, but the local water table. Many hyperbolae have their upper surfaces at about this level: if these are burials, then it would be unlikely they were buried in saturated ground. However, regional ground level is now higher than in the mid 1800s, and in some areas of current-day NW Europe, late winter–spring water tables are elevated from intense winter/spring rain, albeit that these surveys were carried out in dry weather. Ringing hyperbolae are most likely generated from coffins (10,12) as opposed to human remains as the nearby hospital excavation (see "The Problem," above) recovered intact wooden coffins. At the depth recorded, these may be air- or water-filled, creating a dielectric contrast with the surrounding sands and silts. Such ringing hyperbolae are not always coincident with the subsident patches recorded at surface (Figs. 3–5). This is not surprising, as to create the hyperbola in the first place, some upstanding feature in the subsurface must exist. A-shaped hyperbolae, with a bright-spot below (Line 38, Fig. 6*b* and Line 22, Fig. 8) may be indicative of air-filled cavities, possibly within coffins: these two A-shaped anomalies are at around 1.5 m, above the inferred local water-table, yet no deeper A-shaped anomalies occur, perhaps supporting this hypothesis. 200 MHz data in the south-east of the site

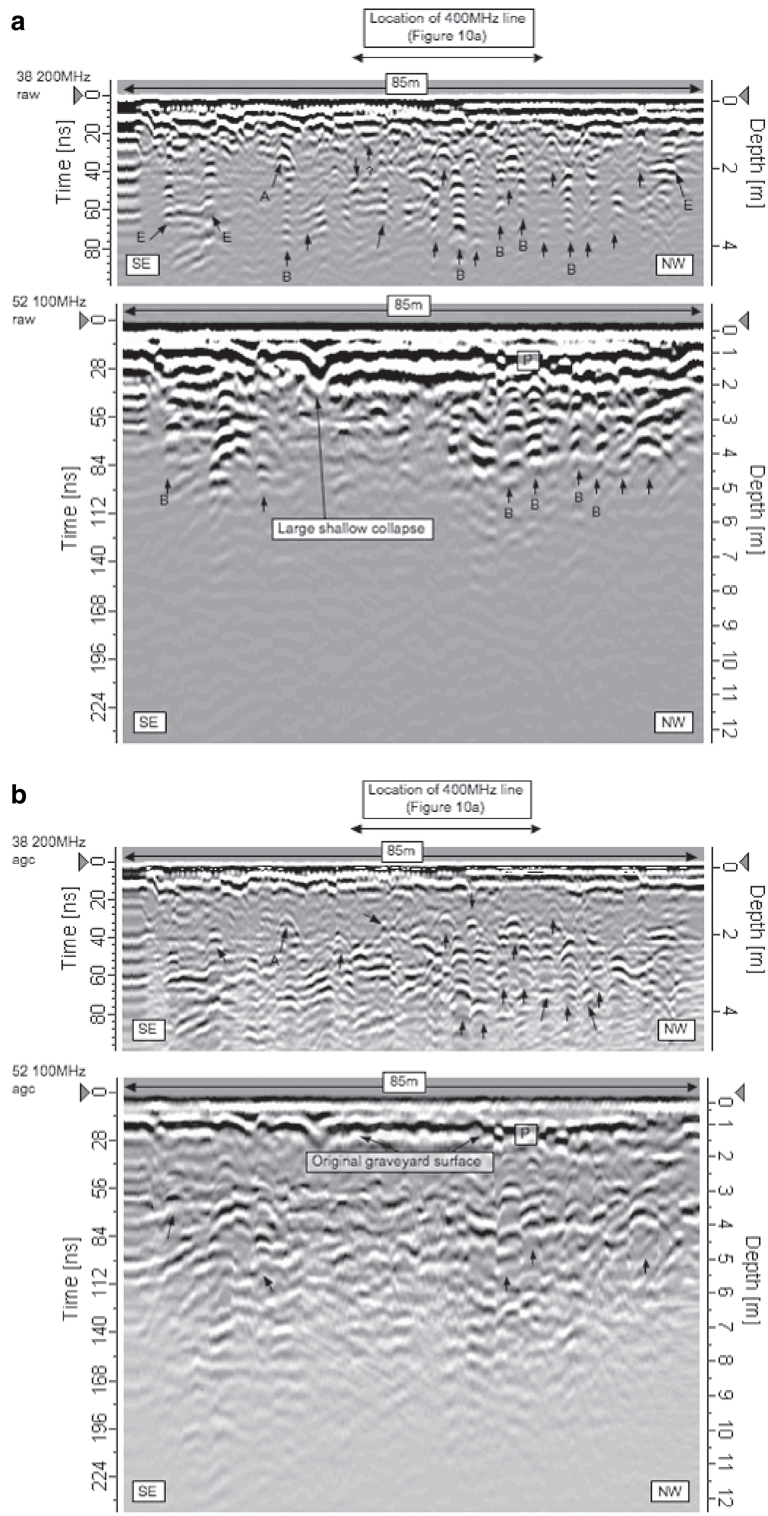

FIG. 6—*(a) Raw (field) 200 and 100 MHz compared. P = interpreted original ground surface, E = elongate reflections, sometimes with ringing below one end, B = ringing hyperbolae, A = A-shaped hyperbolae. Different antennae orientations made little difference to data quality, as out-of-plane features had no effect, yet a parallel broadside configuration for 200 MHz was favored, against a parallel endfire mode for 100 MHz, merely to facilitate antenna movement. (b) 200 and 100 MHz data with automatic gain control applied.*

show a distinct change in fabric from southwest to northeast, with numerous hyperbolae to the southwest, and very few to the northeast. This pattern is reflected in the ground survey, where fewer patches of collapsed ground were noted in the north-east of the site. This change in GPR fabric is coincident with a break of slope observed running southeast to northwest through the site, and interpreted to be a former wall or hedge by virtue of this linear surface feature, the shallow GPR reflections (Fig. 8), and the interpretation of the metal detector indications (see below). In the far southeast of the site a raised reflector at 50–75 cm depth occurs at the north-eastern end of GPR profiles 30 (Fig. 8) and 34 (Fig. 9). The location of this site, away from the original buildings, separate

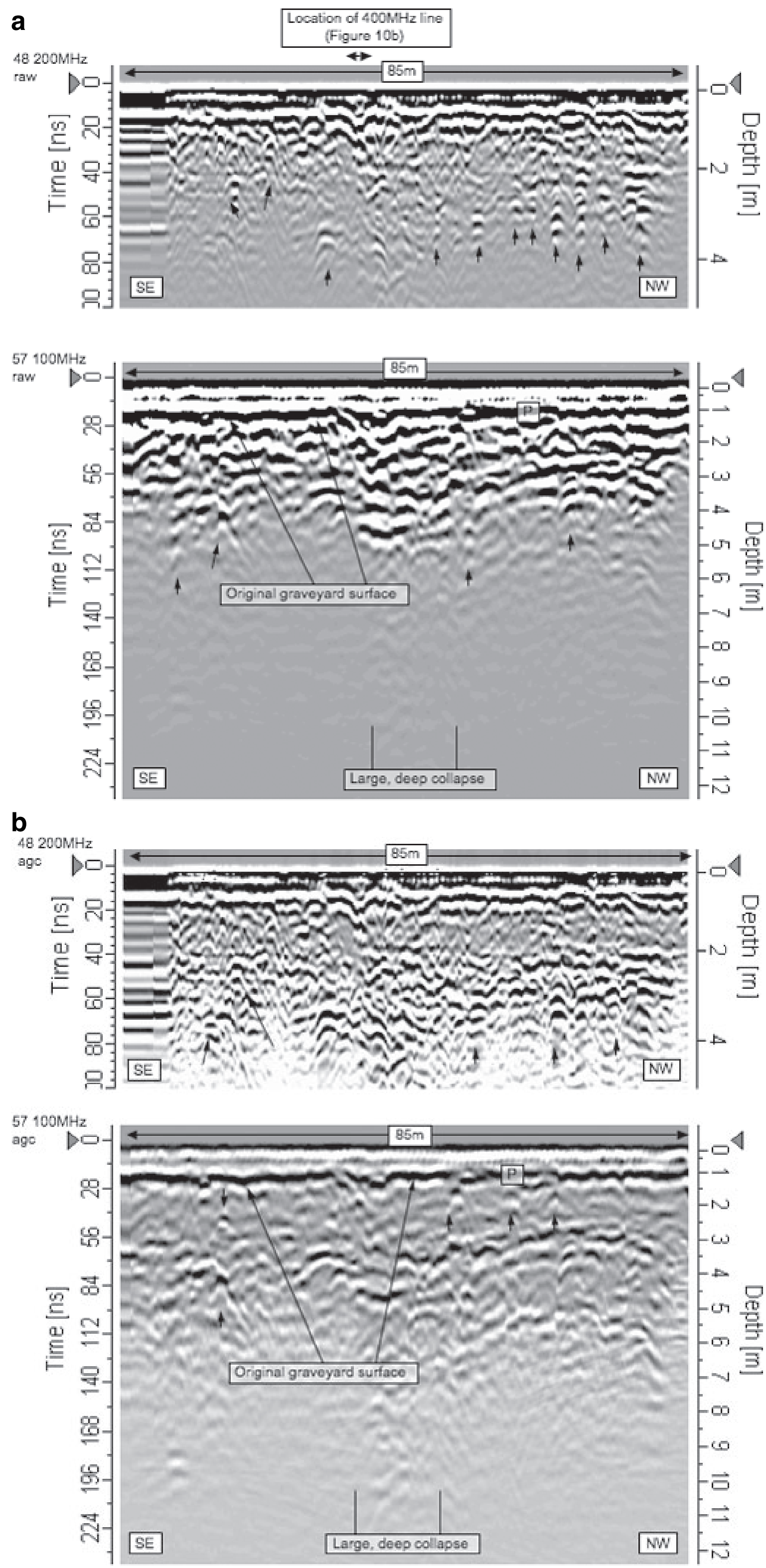

FIG. 7—*(a) Raw (field) 200 and 100 MHz compared. P = interpreted original ground surface. Different antennae orientations made little difference to data quality, as out-of-plane features had no effect, yet a parallel broadside configuration for 200 MHz was favored, against a parallel endfire mode for 100 MHz, merely to facilitate antenna movement. (b) 200 and 100 MHz data with automatic gain control applied.*

from the rest of the graves, is consistent with a kileen, a small graveyard for unbaptized people, most commonly children. Elongate, isolated anomalies (labeled E on Figs. 6*a,b* and 8) may be the long-axis of coffins: these sometimes have ringing hyperbolae centered at one end (Line 38, Fig. 6*a*, NW end; Line 48, Fig. 7*a*, NW end; Line 22, Fig. 8, NE end; Line 28, Fig. 8, SW side). One might expect additional such elongate features on the cross lines of Fig. 8, except the supposed burials are here still being intersected oblique to their axis. These lines were collected with the antennae in a parallel broadside configuration, creating an elongate footprint,

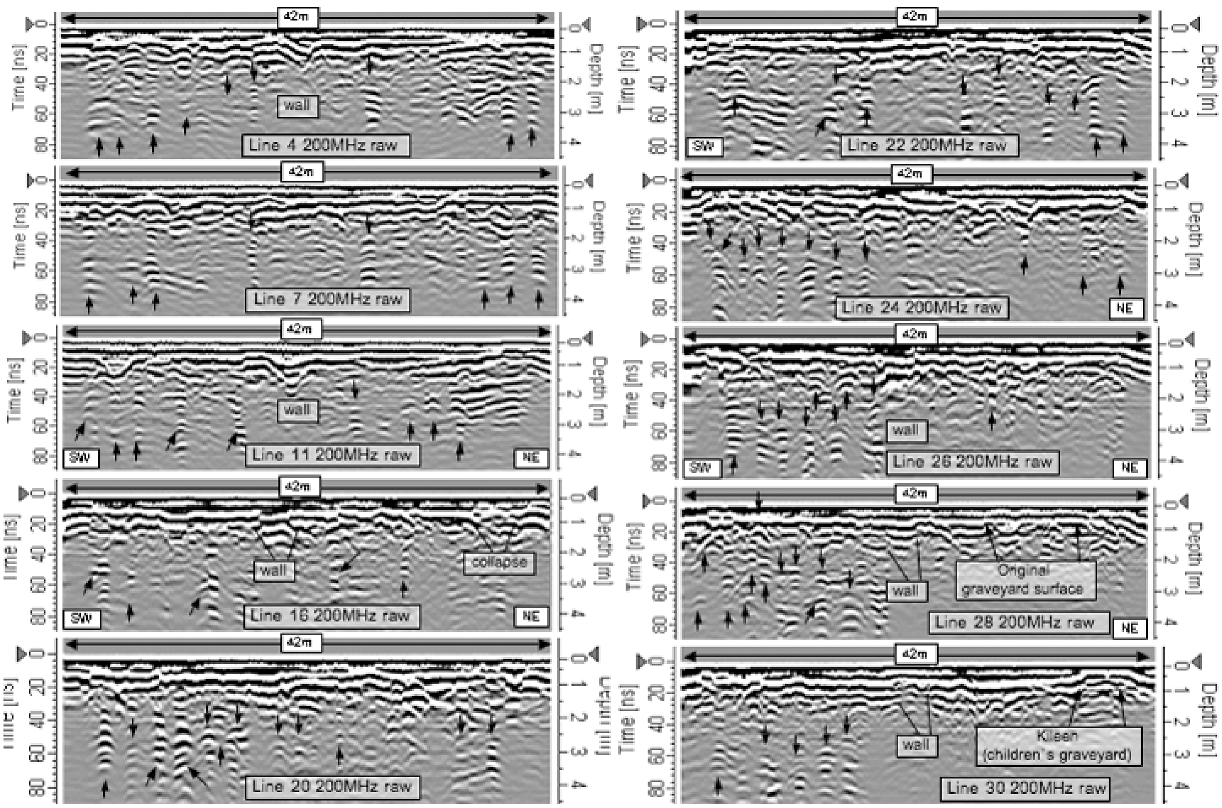

FIG. 8—*Successive 200 MHz radargrams from north to south across the site (Target Area 4). Refer to text for discussion.*

or imaging zone. Thus anomalies will be more likely imaged as point-sources, some of which extend between adjacent GPR lines, suggesting they are elongate features. If such linear features are not double-counted, some 170 anomalies (of all kind) can be reconciled from the 200 MHz data alone. Control lines were gathered from around the site and at nearby locations. A typical example is seen on Fig. 9, where the lack of ringing hyperbolae, A-shaped hyperbolae or elongate, isolated anomalies suggests that these features within the site are not natural (say boulders) and distributed throughout the area. Deep geology was not imaged very well on 100 or 200 MHz data surrounding the site as opposed to within it. This is a curious observation, as the site contains numerous anomalies and disturbed ground, while the surrounding field should be free of such major disturbance, bar ploughing. However, we note that the site has a covering of silt, whilst the surrounding fields comprise soil on clay-rich till. The silt is presumed to be quartz-rich, and may have improved, or focused the signal.

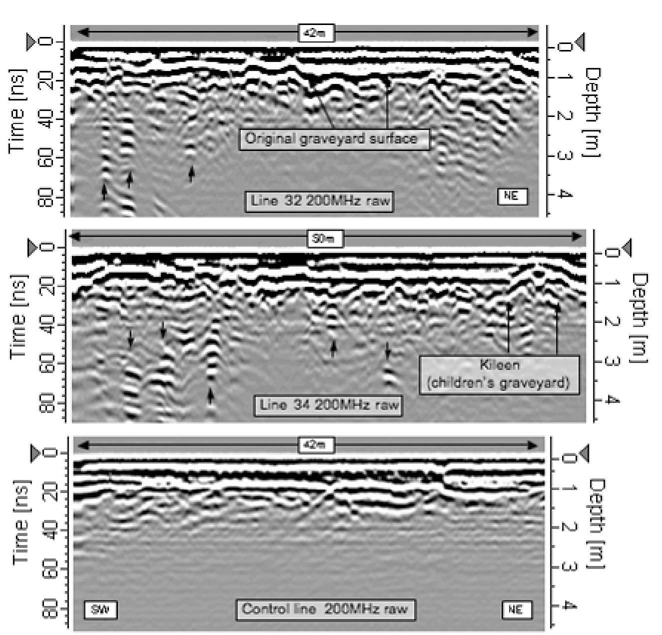

FIG. 9—*Two of the southernmost 200 MHz radargrams compared to a 200 MHz control line from outside the site: note the lack of isolated hyperbola or elongate anomalies.*

400 MHz Data

One of the original aims of this investigation was to assess the number of inhumations within any candidate pauper burial ground. The discrepancies between surface expression, metal detector indications, 100 and 200 MHz data led to suspicion that no one technique was proving failsafe in indicating the presence of these 156-year-old burials. The overall reason for this is that each method is measuring different features at different scales. For this reason, higher-resolution 400 MHz data were collected on a 1 cm stepsize, increasing both shallow and horizontal resolution. The problem with this acquisition method is the increased time of data collection, as great care is required to ensure antenna position, either on a tape measure or using an odometer on uneven grass. Fig. 10*a* shows unprocessed data from over five visually-obvious, shallow (5 cm deep), discrete collapses (Fig. 5), all of which were imaged at different depths. In more problematic ground, where collapses are more cryptic (Fig. 5) only the collapse (no anomaly below) was observed on raw data (Fig. 10*b*). Processing of this data

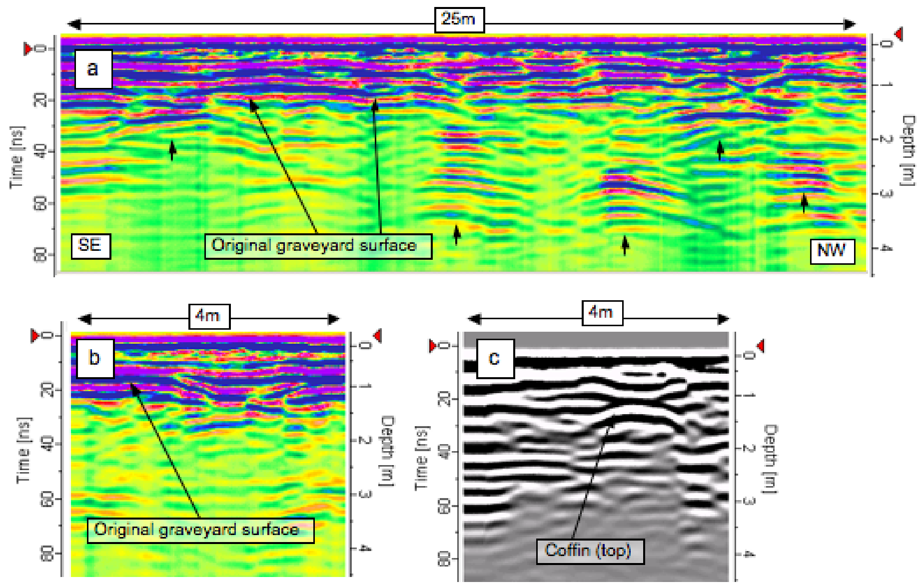

FIG. 10—*(a) Unprocessed 400 MHz data from a control line designed to establish whether higher-frequency antennae may resolve surface features not detected on 200 MHz data (see Fig. 5). (b) Unprocessed 400 MHz data over an individual collapse. (c) Processed 400 MHz data over the same collapse (time varying gain applied).*

resolved a hyperbola consistent with a coffin top. These experiments showed that the surface expressions were associated with deeper anomalies, and that the 200 MHz data may simply have missed such associated features. Likewise, collapses may have some part of the coffin remaining below, as described by (16), but this may not be imaged while in the field.

Integration of Geographic, Ground Survey, GPR, and Metal Detector Data

The current (2007) geography of Target Area 4 shows some attributes that are compatible with historic records and suggested locations for a pauper burial ground. The rectangular site, near to, but isolated from a former workhouse (and possibly other buildings) that existed in the mid-1800s makes the location an ideal candidate. The elongate, east–west orientation of subsident patches of ground are suggestive of Christian burial. The high number of subsident patches to the west of the interpreted wall coincides with a large number of anomalies on the 200 MHz GPR lines, where hyperbolic anomalies are so dense that multiple inhumations must be assumed to be present. These locations have elevated metal detector indications, which together we interpret as a likely reflection of the religion of the victims. Given the population statistics of Ireland in the mid-1800s, we suggest that the western side of the site contains mainly victims of Roman Catholic faith. The fewer supposed inhumations on the eastern side would be Protestants. The metal detector indications were consistent in occurring one-third along the length, and in the middle, of each subsident patch (presumed to be a burial). Without excavation, we do not know the origin of these metal indications, although from the depth and consistent location, these are not coffin nails or random artefacts. We propose that they may come from associated artefacts (rosary, crucifix), or from crucifixes attached to the coffin. Why some "graves" on the Protestant side have metal detector indications is unknown, although it is intriguing that the kileen (non-baptized victims) is on this side of the site. If the interpretation of a wall, dividing the site, is correct, its depth on radar data suggests it may have post-dated the burials. Other possibilities are that this was a pathway or hedge-line. The boundaries of the kileen may also have been a small wall or hedge. Following the initial hospital excavation of a few individual pauper graves, an estimate was made for the as-then unlocated site having some tens of victims within it. Once discovered through critical evaluation of historical records, reconciled with aerial photographs and landscape interpretation, Survey Area 4 was surveyed. At this point 84 possible burials were noted. 100 MHz GPR data showed indications of some possible burials, where characteristic hyperbolae could be observed. These were also observed on 200 MHz data, along with many more anomalies that could be burials. Some of these were coincident with subsident ground, many were not. Some anomalies on adjacent profiles are undoubtedly the same feature, although these rarely extend across more than three profiles, making them consistent in the 1–2 m lengths (given the imaging "footprint" of the radar detection at depth) with the subsident ground. Over 170 anomalies were observed on the 200 MHz lines, about half of which were below surface indicators. The prediction of tens of inhumations could now be elevated from the 84 surface indicators to around 210 patches of subsident ground and/or GPR anomalies. This lack of consistency between the two datasets is reconciled by the 400 MHz survey, which showed that the subsident patches were indeed consistent with burials and thus the 200 MHz surveys "saw" some burial-associated anomalies outside of the survey line (footprint effect) but likewise probably missed many potential targets. As 200 MHz GPR anomalies coincided with only half (50%) of the surface expressions, another 50% of the estimated burials may exist—making a possible total of over 300 burials. This excludes what may be in the collapsed ground on the eastern side of the site, which although probably geological in nature, is suspicious as such collapses are associated with limestone caverns, mining, and human activity rather than the post-glacial sands, glacial till, and Carboniferous sandstones present under Target Area 4. A glacial pingo or kettle-drum may cause such a feature, but to be present at shallow (1 m on Line 16, Fig. 8) and deep (5–12 m on Line 57, Fig. 7*a*) is anomalous and requires cautious excavation.

Conclusions

This study has replicated many of the procedures encountered during the search for, and investigation of unmarked war-time, epidemic, and clandestine burial sites. Let us take an example: a burial site is known somewhere through local intelligence (e.g., genocide) disaster monitoring (e.g., seismology), or historical records (e.g., this study and war-graves investigations). The location of recent mass burials may be obvious by the location of landslides, tsunami deposits, known individual graves, or require remotely-sensed satellite or aerial photography (near-infrared, ultraviolet) for location. Where burials are too old to provide a thermal (17), vegetational or reworked ground signature, or where remotely-sensed data of required resolution cannot be obtained (cost, security) then geographic analysis of maps, historic aerial photography, and ultimately walk-over are required. Gomez-Lopez & Patino-Umana (18) consider just this scenario, where in Colombia, satellite imagery was used to define landscape types and then concentrate on individual locations. The current study is an example of this latter situation, one which may not have the media attention of recent war-graves or natural disasters, but which with peace and reconciliation ongoing in many countries, is increasingly important. Our realistic view of (possibly inaccurate, and rather sketchy) historical information focused the search for a cemetery of certain shape, location, and likely size. Using aerial photography, a likely site was quickly located, reducing the time required for surveys on foot: one other site had no sign of a graveyard and two others were small and with gardens and buildings within them. The target site had over 8 times the predicted possible burial sites, from visual estimates alone. This caused some problems with local residents and the media, and demonstrates how careful the forensic geoscientist/forensic anthropologist needs to be, even with burials over 150 years old. Interpretation of 200 MHz GPR data showed no anomalies that could be burials outside of the target area, yet nearly double the estimate of graves made by surface evaluation only. Experiments with 400 MHz antennae showed the 200 MHz data likely missed many burials, or they were not detectable on the grid spacing and antennae frequency. A combined interpretation of surface features (collapses, breaks of slope), metal detector indications, and GPR data provides an image of multiple inhumations to the west of the site, possibly containing Roman Catholic victims, with a wall or structure separating them from far fewer, possibly Protestant victims. A feature consistent with a graveyard for unbaptized victims (mostly children) occurs in the southeast of the site. Other anomalies are identified that require further investigation (e.g., the large collapse). Geographic, geologic, and geophysical investigation also shows that the graves occur at a likely local water table in permeable sands and silts, with a low regional slope to the south. A full hydrogeological investigation is required in order to assess the effect of the likely 200+, 150-year-old, formerly diseased cadavers in the site has had on shallow and deep groundwater.

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