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Ground Penetrating Radar Surveys to Locate 1918 Spanish Flu Victims in Permafrost

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ABSTRACT: The "Spanish Flu" killed over 40 million people worldwide in 1918. Archival records helped us identify seven men who died of influenza in 1918 and were interred in Longyearbyen, Svalbard, Norway, 1300 km from the North Pole. Ground Penetrating Radar (GPR) was used successfully, in a high-resolution field survey mode, to locate a large excavation with seven coffins, near the existing seven grave markers. The GPR indicated that the ground was disturbed to 2 m depth and was frozen below 1 m. Subsequent excavation showed that: a) the GPR located the position of the graves accurately, b) the coffins were buried less than 1 m deep, and c) that the frozen ground was 1.2 m deep where the coffins were located. The GPR assisted in planning the exhumation, safely and economically, under the high degree of containment required. Virologic and bacteriologic investigations on recovered tissues may give us an opportunity to isolate and identify the micro-organisms involved in the 1918 influenza and expand our knowledge on the pathogenesis of influenza.

KEYWORDS: forensic science, ground penetrating radar, geophysical survey, Spanish Flu, 1918 Spanish Flu, permafrost, archaeology, graves, Longyearbyen, Spitsbergen, Svalbard

A serious outbreak of influenza occurred in the eastern United States of America in 1918. It developed into a full pandemic, spreading worldwide in a matter of months (1). Unusually, the outbreak caused significant loss of life among young adults, in the 20 to 40 year age range. The identity of the 1918 "Spanish Flu" agent remains largely unknown, since human influenza virus was not isolated until 1933 (2). Recent studies, based on archived, formalin fixed tissue samples, have provided limited sequences for four of the eight virus genes, (3) but no insight as to the cause of the virus's high pathogenic potential. It is possible that the high pathogenesis resulted from a complex interaction of virus and bacteria (4,5).

An extensive search through death records of Arctic regions, for the last half of 1918, identified very few sites where the locations of the graves of victims of the "Spanish Flu" were known and where permafrost conditions were favorable for full preservation of the bodies. The most promising site identified was a cemetery located in Longyearbyen, Svalbard, (78°N latitude, 15°E longitude), approximately 1300 km from the North Pole. Figure 1(a) is a map of the Arctic; and Fig. 1(b) shows the location of Longyearbyen on the Island of Spitsbergen in Svalbard. Seven Norwegian miners, aged between 19 and 28, died of influenza during September and October 1918 and were buried in the cemetery near Longyearbyen. Permission was obtained from the Norwegian authorities to exhume six of the seven bodies for sampling.

In preparation for exhuming the six bodies, a detailed, non-invasive, geophysical survey of the grave site and its environs was carried out to determine: (a) the precise location and dimensions of the grave(s); (b) the probable depth of the graves; and (c) the depth of the permafrost active layer, the surface layer of the ground which undergoes freeze-thaw on an annual cycle, at this site. A high-resolution ground penetrating radar (GPR) survey was used successfully to locate the graves. Preliminary results of subsequent excavations at the site are discussed. GPR has significant application for mapping fine detail in archaeological and forensic pathology applications and for planning safe and economic exhumations under a high degree of isolation.

Site Description

The Longyearbyen Cemetery is located about 1 km south of town. The cemetery is on a 1:4 slope, facing southeast, that receives sunshine earlier in spring than most areas in the valley. The graves are in the form of plots, raised some 10–20 cm above the natural ground level. Figure 2(a) shows a plan of part of the cemetery, where there is a total of 31 marked graves. The marked graves of the seven miners are located in the northwest corner of the cemetery, on Row 1, between grid positions −9 and −12 m north and 6 and 12 m east. It is known that the crosses have been replaced at least once since 1918. The cemetery perimeter is marked by a low stone kerb, which is partially visible along the western and southern sides. A perimeter fence, made of chain, supported on iron

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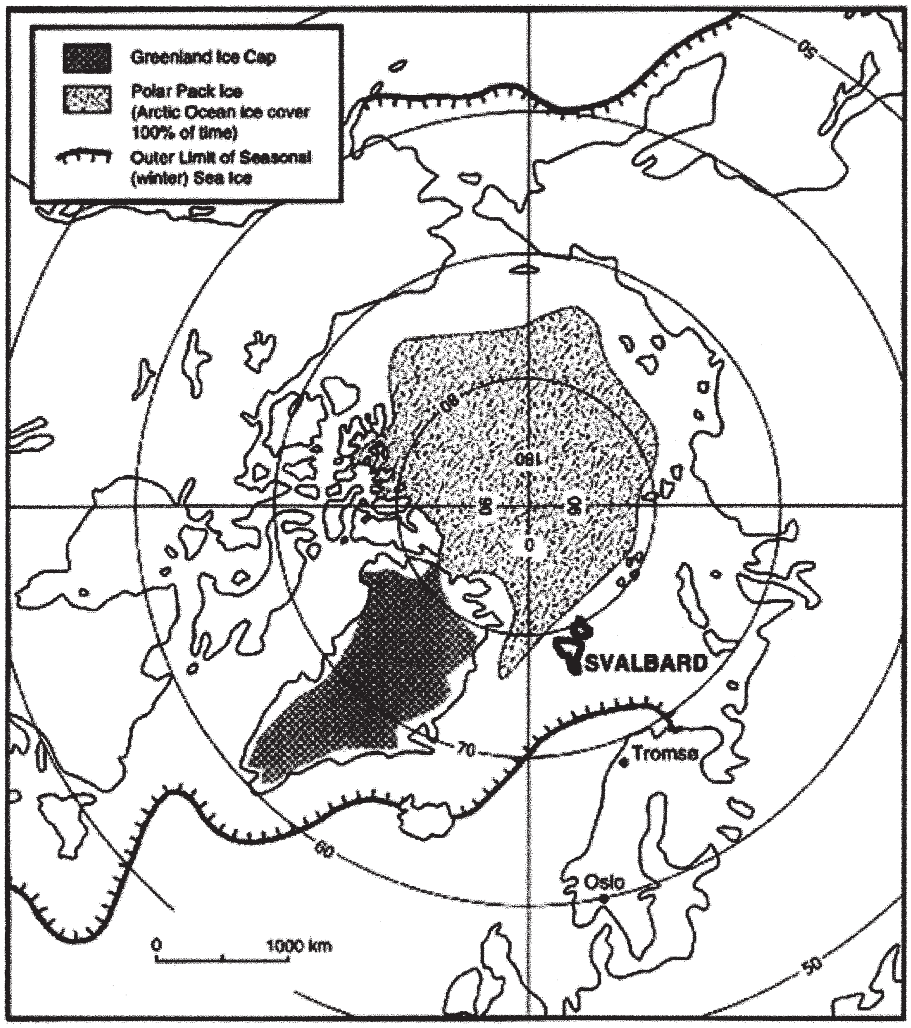

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FIG. 1—*Location of Svalbard:* (a) *the archipelago of Svalbard lies about 1300 km from the North Pole and 650 km north of Norway;* (b) *Longyearbyen is on the Island of Spitsbergen, on the south side of Isforden and some 60 km from the open sea.*

posts (drill rods) was erected in 1961.

The cemetery is sited on 2 to 3 m of till soil overlying bedrock. The texture of the soil in the area ranges from angular boulders up to a few decimeters in size, to clay. There are indications nearby of downslope movement of the active layer, by creep or solifluction processes, over the frozen soil below. The vegetation comprises mosses, grasses and forbs, plus crustose lichens on many of the exposed boulder surfaces.

GPR Method

GPR sends a few nanosecond long pulse of radio-frequency energy into the ground. Part of the signal is reflected whenever it encounters changes in the electrical properties in the ground and this is detected on the surface. Practically, the signal velocity and electrical conductivity describe the propagation of the GPR signal in the ground. Knowing the signal velocity (v) allows the travel time (t), measured by the GPR, to be converted to a depth (d) scale from the following relationship:

$$d = \frac{tv}{2} \tag{1}$$

The velocity can be determined either by correlating the GPR reflectors to known materials in the ground, or by Common Mid Point (CMP) velocity soundings, where the antennas are moved apart from each other over reflectors of interest (6,7). Knowing the antenna separation (x) the velocity is determined by:

$$v = \frac{(x^2 + 4d^2)^{1/2}}{t} \tag{2}$$

The soil volumetric water content, affected by soil grain size and density, is the major determinant of the signal velocity (8). The phase of the water molecules, whether liquid or solid, also affects the signal velocities of soils (9). The principles of GPR are discussed elsewhere (10).

GPR is different from conventional radar in two ways; first, GPR "looks" into the ground and second, the GPR is moved past the target of interest whereas with conventional radar the target moves in air relative to the radar system. The radar signal velocity is 0.3 m/ns in air, whereas in the ground, the signal velocity ranges from about one-half to one-ninth the velocity in air. The attenuation is the rate at which the signal amplitude decreases with distance. The attenuation in air is negligible, whereas in the ground it varies widely, from almost zero in ice, dry and frozen sands and gravels to many

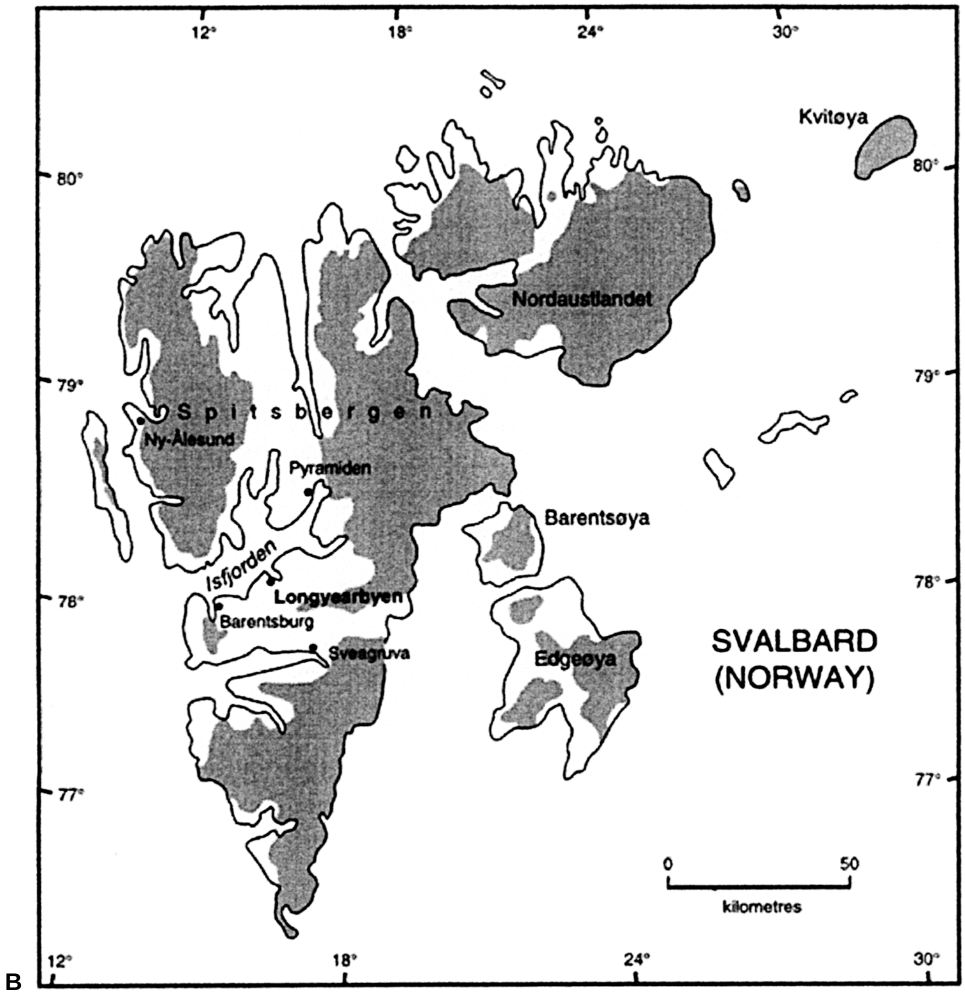

FIG. 1—(*Continued*).

orders of magnitude in silts, clays and other electrically conductive materials like sea water and contaminated soils. The attenuation (α) in dB/m, is related to the electrical conductivity (σ) in mS/m and the velocity (v) by the following:

$$\alpha = \frac{(1.69*10^3)\sigma v}{c} \quad (3)$$

where c is $3*10^8$ m/s, the velocity of an electromagnetic wave in space. CMP soundings can give a qualitative estimate of the signal attenuation in the ground from the radar range equation (11) and the penetration range of the GPR at the site. These differences make the GPR equipment design and survey methods significantly different from conventional radar systems.

In the reflection sounding mode, the GPR is moved over the ground and data traces are collected at close spacing along the profile line. The data traces are displayed side-by-side in a vertical section with the GPR position along the horizontal axis and the signal travel time or depth on the vertical axis. The data are displayed in the field both for quality control and preliminary interpretation. This permits the survey to be optimized in the field.

The vertical section data presentation is difficult to visualize compared to plan-view presentations. There have been significant advances in both the data quality of digital GPR equipment and in the speed of data acquisition and processing (12). These advances permit the GPR data to be presented in plan and in 3-D. These data presentations require that the GPR data be collected in the field at close spacing and with good positional accuracy for each data trace over the search area.

The spacing between traces, both along the survey line and the spacing between the survey lines, is linked to the center frequency of the antennas and the signal velocity in the material being sounded. The Nyquist sampling interval should not be exceeded to assure that the ground response is not spatially aliased. The Nyquist sampling interval (n_x) in m, is one-quarter the wavelength in the host material, given by the following:

$$n_x = \frac{(v*10^3)}{4f} \quad (4)$$

where f is the antenna center frequency in MHz and v is the velocity in m/ns. The data will not adequately define steeply dipping reflectors if the station spacing is greater than the Nyquist sampling interval. The criterion can be compromised in areas where the reflectors are expected to be flat lying.

In the field, it is practical to keep the trace spacing along the survey line, equal to or less than the Nyquist sampling interval. Usually, due to limited time to run the field survey, the spacing between survey lines is set greater than the maximum Nyquist interval. This is acceptable in applications where the target is longer in one direction and the lines are oriented perpendicular to the long axis. Survey design is discussed in detail elsewhere (13). Collecting GPR data for high-resolution, detailed presentations, as was done here, is necessary to locate old graves which may only have subtle soil disturbances in relatively localized areas on the order of 1.5 by 0.5 m.

GPR Equipment

A Sensors & Software Inc. pulseEKKO™ 1000 GPR system with 225, 450 and 900 MHz center frequency antennas was used for this survey. The lower the antenna frequency, the greater the depth range, and the higher the frequency, the greater the depth resolution. It is necessary to determine the highest frequency that can penetrate to the depth required. Based on preliminary tests and the understanding that the graves would be 2 m deep, it was determined in the field that the 225 MHz antennas were required. An odometer was used to trigger the system at a fixed spacing along the survey line.

Survey Methods

A 1 m by 1 m square survey grid was laid out over a 25 m by 23 m area centered on the northwest corner of the cemetery. Figure 2(a) is a sketch showing the grid and the positions of the graves and markers in the cemetery. The seven graves of the seven Spanish Flu victims are located in the northwest corner. A line through the south side of the seven markers of the Spanish Flu victims that died in October 1918 was labeled Line −10 north and the west perimeter chain fence was Line +5 east on the grid. Over 70 GPR reflection survey lines were run, at 0.5 m spacing where possible, in both north-south and west-east directions, as shown by the thin lines on Fig. 2(b). A GPR trace was collected every 20 mm along all the lines, to ensure that localized responses from any disturbed ground at the graves would be shown on the data. Each trace was averaged four times to reduce the interference from local communications.

Seven common mid-point, CMP, velocity soundings were also collected, both over and away from marked grave areas, as indicated by short heavy lines in Fig. 2(b). The CMP on Line −11.2 m north was run with both the 225 and 450 MHz antennas. All the field GPR surveys were completed in a five day period during October 1997.

Data Processing and Interpretation

The GPR data were interpreted to address the research questions identified in the introduction. The first step was to interpret the CMP data to determine the GPR signal velocity in the ground, so that the signal travel times could be converted to a depth scale. Using the interpreted CMP results, it was then possible to estimate the probable depth of the active layer and the depths of the excavations and possibly even the graves. Finally, the location of the seven graves was plotted from interpretations of all the profiles. In particular, plan-view plots were made of the scattered signal amplitude over a selected depth range after signals from continuous layering in the soil were removed. Three-dimensional presentations

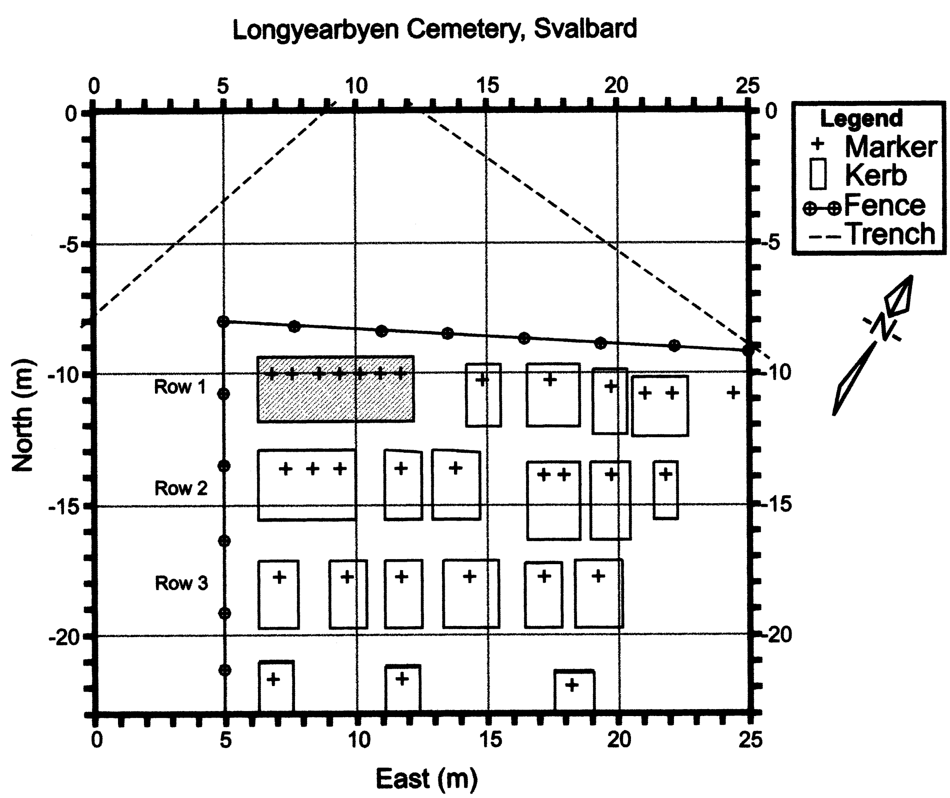

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FIG. 2—*Layout of the Longyearbyen Cemetery:* (a) *a plan of the cemetery, showing surface features of the site and* (b) *GPR survey lines centered on the northwest corner where the thin lines indicate the reflection survey lines and the short thick lines show the CMP locations. The hatching shows the marked graves of the seven Spanish Flu victims in the northwest corner of the cemetery, on Row 1, around grid positions, −10 m north and between 6 and 12 m east.*

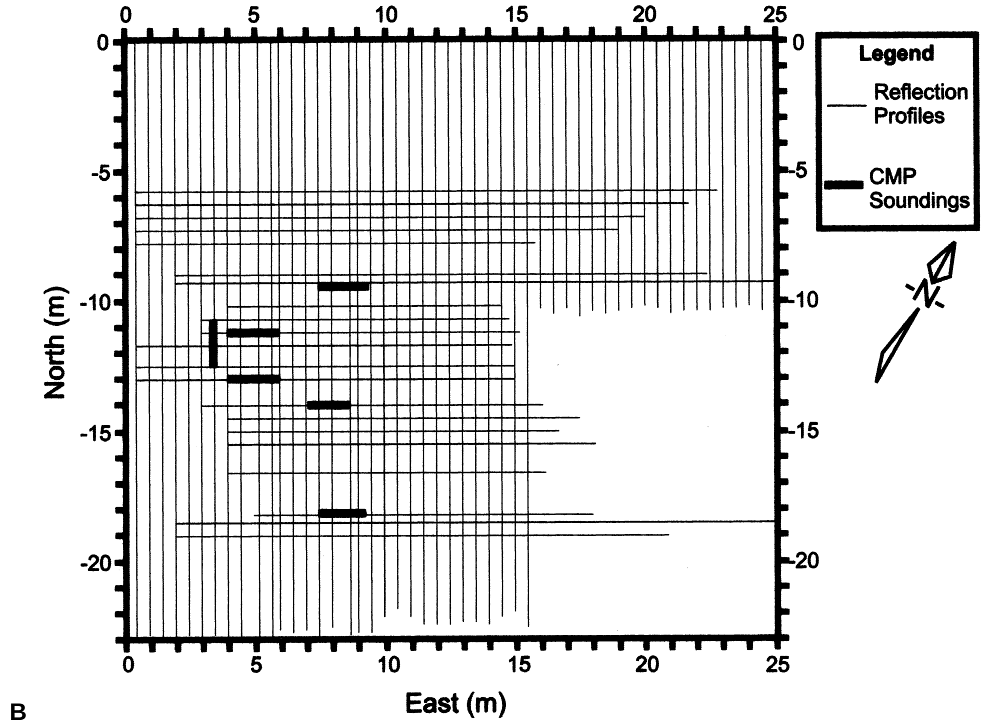

FIG. 2—(*Continued*).

did not help significantly to show the positions of the disturbed ground compared to the plan-view presentation.

Knowing that the scattered signals could also be from natural geological changes in the ground, like changes in soil type or a zone of boulders in the soil, an additional interpretation method was required. It was necessary to think of some additional feature which is unique to man-made excavations. Often the edges of excavations in the ground show on the GPR data as dipping reflectors near the ground surface. The near surface reflections on the GPR data were manually interpreted and the result was placed on a plan–view plot and compared to the plan-view plot of the scattered signal amplitudes. The comparison of these different views of the data resulted in a high confidence level for the location of the graves. This high confidence was also possible because of the high resolution, detailed field survey with crossed survey lines and small spacing between the survey lines.

Results

Velocity Measurements

The seven CMP soundings identified two layers at the cemetery. The upper layer at the ground surface had a thickness of 0.8 ($\pm$0.1) m and a velocity of 0.10 ($\pm$0.01) m/ns, which is typical of unfrozen, unsaturated glacial till soils. The estimated electrical conductivity in this layer was between 30 and 50 mS/m, which is equivalent to an attenuation of 5 to 10 dB/m, which is also typical of an unfrozen soil with clay. This layer was interpreted as being the permafrost active layer. The deeper layer had a signal velocity of 0.14 ($\pm$0.02) m/ns, with a conductivity of a few mS/m or an attenuation of about 1 dB/m, which is typical of frozen soils. Measurements were made in October, when the active layer was expected to be at its deepest for 1997.

Temperature History

Study of air temperature records for 1912–1998 in the Longyearbyen area, published by The Norwegian Meteorological Institute, Oslo, shows that the average temperature of about -6.5°C, for 1997 was similar to the average temperature for the years since 1918. This suggested that the depth of the active layer was unlikely to have been deeper than about 1.2 m over the past 80 years (14). Further, it is estimated that the ground temperature at 2 m depth has ranged between -4 and -6°C.

Plan of Scattered Signal Amplitudes

GPR is sensitive to changes in the layering of soils and digging will alter this. Plan views, showing increased GPR reflections in the ground, interpreted as indicating disturbance of the natural layering of the soil, can be used to indicate the locations of the excavations made for the graves. Figure 3(a) shows the GPR record, along Line -18.2 m north, on Row 3, (Fig. 2a) over graves made after 1925. The positions of grave edges (kerbs) and grave markers observed on the surface are indicated on the data record. There are GPR reflections from 1.5 to 3.0 m depth between positions 6.5 and 8.0 m, 9.0 and 10.0 m, 11.5 and 12.5 m, and 14.5 and 15.5 m along the line. These locations agree well with the positions of the marked graves, on the surface.

Figure 3(b) is a GPR record, along Line -11.2 m north, on Row 1, (Fig. 2a) over the marked graves of the Spanish Flu victims. The positions of the grave markers are shown on the data record. There are many GPR reflectors from the surface to 2.5 m depth between 7.0 and 12.5 m along the survey line, which agrees well with the positions of the grave markers on the surface. There are also similar strong GPR reflectors in the ground between 3.0 and 6.5 m, located outside the marked cemetery boundary, which may be from unmarked graves.

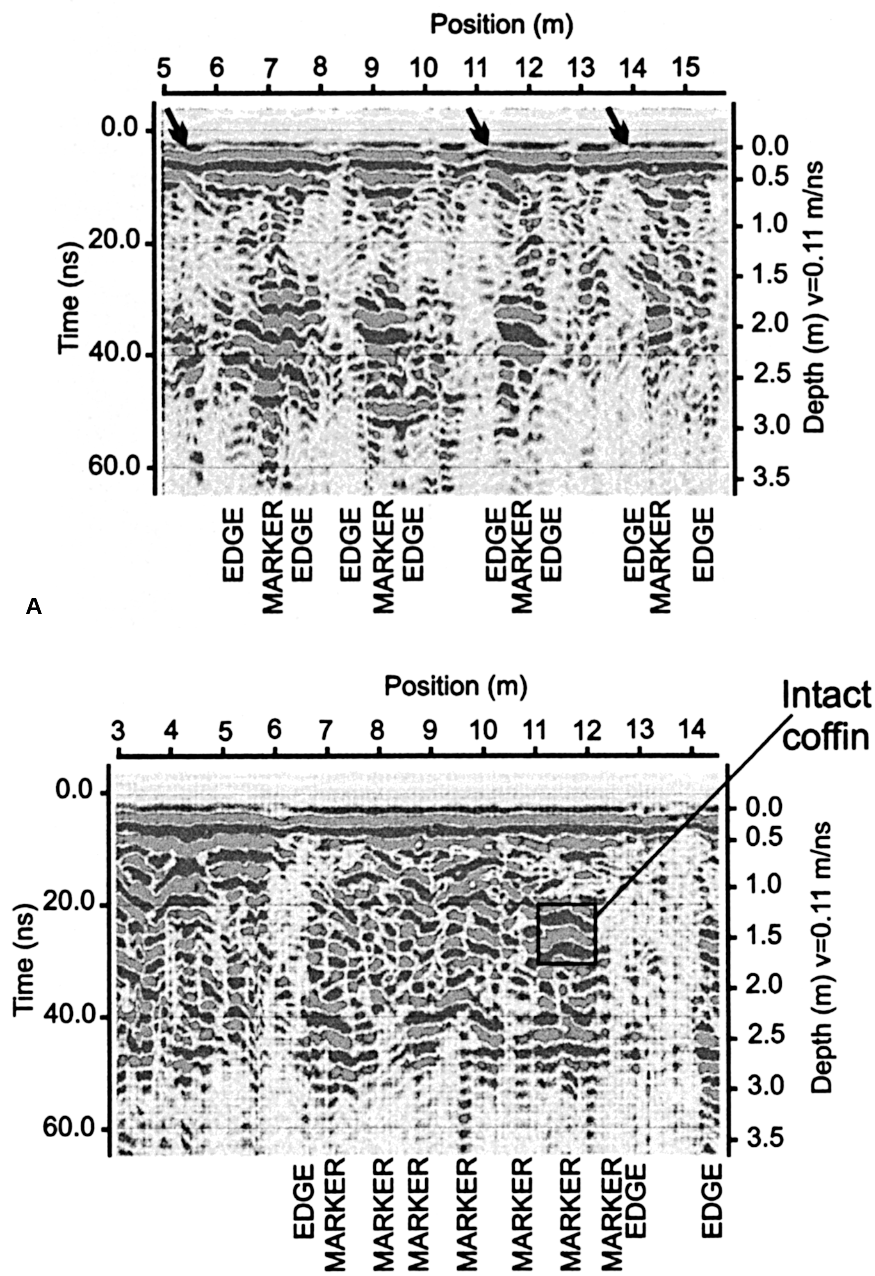

FIG. 3—*The GPR record along lines running west to east over graves at:* (a) *−18.2 m north; along Row 3 and* (b) *−11.2 m north, along Row 1, the grave of the Spanish Flu victims. The excavation showed that there was only one intact coffin and the GPR response from this is shown in the rectangle on 3*(b)*. The arrows indicate examples of dipping reflectors from the sides of excavations.*

Dynamite was often used to loosen the frozen soil for excavation and this would account for the ground being disturbed to 2 m depth, the standard depth of burial in Norway. Such an excavation procedure helps to account for the GPR reflections extending from the surface to 2 m along Line −11.2 north (Fig. 3b), with the coffins placed only a meter deep in the disturbed ground compared to the responses from the graves along Line −18.2 north (Fig. 3a), with the coffins at 2 m depth and the soil column carefully repacked. Thus, it appeared that the bottom of the excavations were at least a meter below the active layer.

Given that the graves were expected to be at a depth of about 2 m, the reflected signal amplitudes from between 1.5 and 2.3 m were plotted. Figure 4(a) is a plan showing areas of strong reflectors as black or dark shading and areas with weak or no reflected signals as light shading or white. The surface plan of the cemetery (Fig. 2a) is also shown. Areas of strong reflected signals along Line −15 and −19 m north agree well with the positions of the grave markers. An area of strong reflectors along Line −11 m north, between −9 and −12 m north and 6 and 12.5 m east, coincides with the grave markers of the seven influenza victims. Other areas of strong reflectors, outside the marked cemetery boundary, are located to the west, between −10.5 and −12.5 m north and 3 and 6 m east, and to the north around −8 m north and 18 m east. These areas are similar in size and signal amplitudes to that marked for the influenza victims.

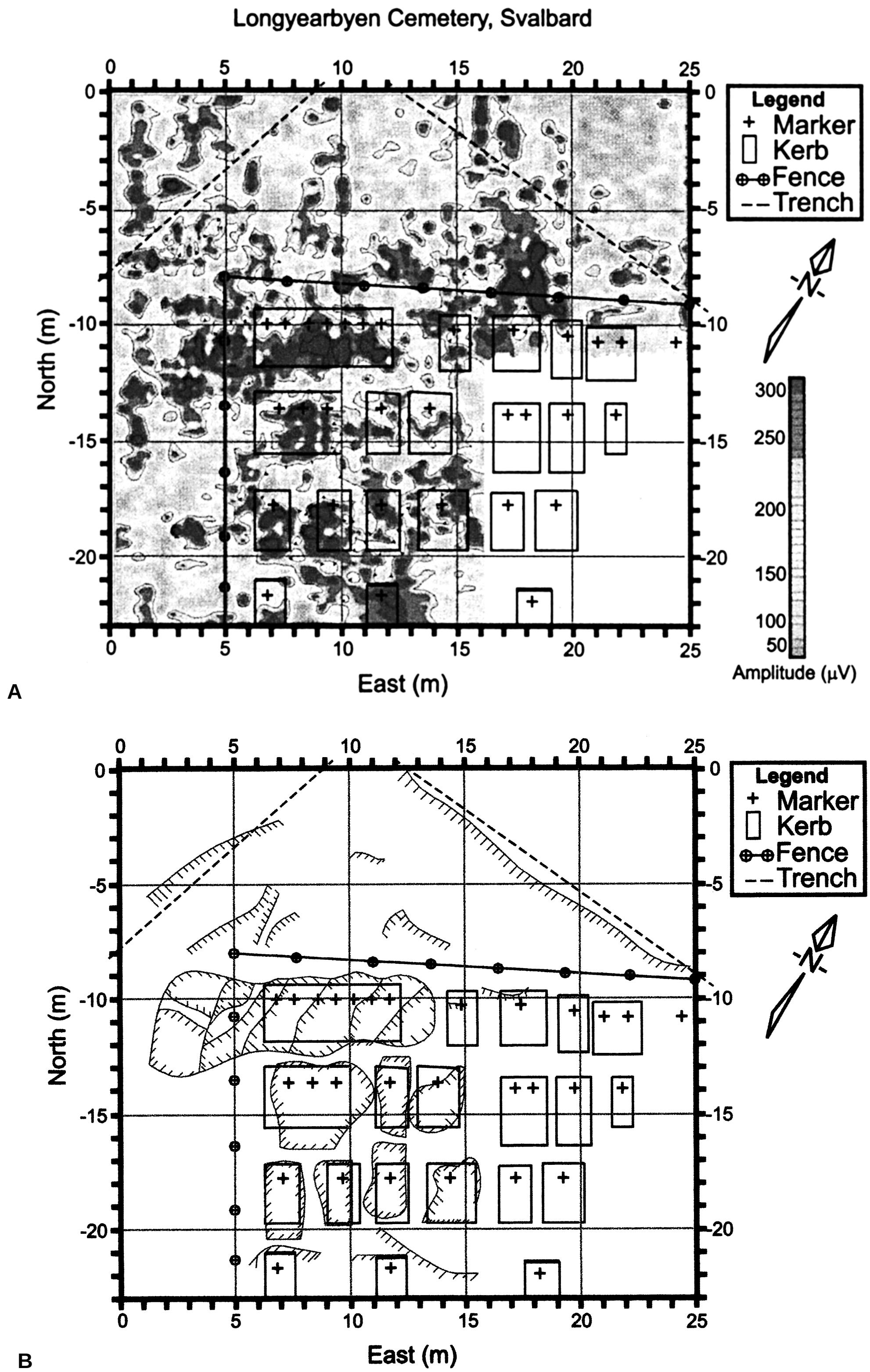

FIG. 4—*Plan of the area surveyed by GPR, showing:* (a) *a gray-level contour plot of reflected signal strength for reflectors at depths between 1.5 and 2.3 m;* (b) *locations of dipping reflectors that are from the sides of excavations.*

Additional interpretation of the GPR data was required to distinguish between strong reflectors from graves and natural geological variation like boulders in the soil.

Plan of Near-Surface Dipping Reflectors

The edges of excavations for graves often appear on GPR data as near surface, dipping reflectors. Although the data were processed to enhance horizontal reflectors, examples of near surface dipping reflectors from the edges of marked graves along Line −18.2 m north can be seen at 5.5 m and 14 m (Fig. 3a). The dipping reflectors are shown on Fig. 4(b) with the hatching indicating the direction of dip. There is excellent agreement with the locations of the marked graves along lines at −15 and −19 m north. Along the line at −11 m north, there is a large area of dipping reflectors, coinciding with the markers for the Spanish Flu victims, and this area extends to the west as identified earlier (Fig. 3b). No dipping reflectors were seen on the GPR data in the area near −8 m north and 18 m east, indicating that these reflectors are probably of geological origin.

Discussion

The high-resolution GPR survey methodology and a combination of interpretation techniques of the data were used to locate the graves of seven coal miners who died of influenza in Longyearbyen, Svalbard, in October 1918. Excavation of the graves, in August 1998, showed that the GPR interpretation of the location of the graves of the seven miners was accurate.

Furthermore, the GPR showed that the ground was disturbed from the surface to 2 m deep along Row 1 (Fig. 3b). This was different to the later graves along Row 3 (Fig. 3a) but this may be attributed to the use of dynamite to loosen the frozen soil. It should be noted that the GPR could not resolve the actual coffins because the 225 MHz antennas had been used in order to penetrate to 2 m, the expected depth of burial in Norwegian cemeteries. The 450 and 900 MHz antennas offered higher resolution but field tests along Row 1 indicated that no signals below 1 m were detected with these antennas.

GPR can detect the voids in wooden coffins if they have not collapsed. It is difficult for GPR to detect collapsed coffins especially when they are filled with soil, since there is little contrast in the electrical properties of the materials. It is also difficult to detect bones because they are physically small and they have similar electrical properties to dry soil. Collapsed coffins and bones are almost impossible to detect if the signal attenuation is high such as in electrically conductive soils like clay. The chances of detecting subtle changes in the ground improves as the attenuation in the material decreases and as the GPR frequency is increased. The disturbed ground at this location causes the signal to be scattered, much like fog at optical frequencies, and thus it makes it more difficult to resolve coffins.

The excavations showed that the coffins of the seven Spanish flu victims were at a depth of less than 1 m. All the coffins were placed next to one another and only one coffin was intact whereas the others had collapsed and filled with soil. Knowing this, it is now possible to identify the intact coffin on the GPR data records, as the thicker four bands shown in the rectangle on Fig. 3(b). This response is similar to the interpreted responses from the graves, at 9 and 12 m east and 2 m depth, on Row 3 (Fig. 3a). This illustrates how important it is to use all available information when interpreting geophysical data, but shows also how critical it is to recognize the limited reliability and accuracy of information based on oral history or long term memory that cannot be corroborated by documentary or physical evidence.

It was observed during excavation and on the GPR, that the soil below the coffins had been disturbed in the past. We speculate that the ground had been loosened to a depth of 2 m by dynamite but the coffins had been placed less than 1 m deep because of the difficulty in digging in the frozen ground during the exceptionally cold October of 1918. In addition, the miners may have feared the unknown disease that killed the seven fellow miners. This fear may have been increased considering the accounts from the south of the severity of the flu epidemic (15) and further, that it would be at least six months till the next boat would sail to the isolated mining camp with medical supplies. Under these conditions, it is perhaps not too surprising that the coffins were not buried 2 m deep.

The active layer was measured at 1.2 m in the area where the coffins were located whereas, from the GPR data, the depth of the active layer in October 1997 was estimated to range between 0.7 and 1.0 m with an average of 0.8 m. The lower soil density and the additional GPR reflections where the coffins were located can account for this difference.

The primary objective of our study is to recover virus RNA to confirm and augment the nucleotide sequence analysis of material from formalin-fixed tissue reported recently (3). The morbid pathology of victims of the 1918 pandemic was novel and suggestive of a pneumonitis. Co-infection with certain bacteria can increase the pathogenicity of influenza (16). Therefore, a broad-spectrum antigenic and nucleic acid analysis of respiratory tract bacterial material will also be undertaken in addition to the virological analyses. Samples of tissue, recovered from the six bodies, are being used for these studies and the results of this phase of the project will be presented elsewhere in due course.

Although GPR has been used by archaeologists (17–19) and forensic pathologists, our detailed survey, used to locate graves in permafrost, is unique. Since these bodies may harbor infectious agents, knowledge of their precise location was essential to allow sampling under the high degree of containment required. Further, by minimizing the extent of the excavation process, the restitution of the Longyearbyen Cemetery, which is a heritage site, to its original condition was made easier.

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