

funded by the European Union's 10-year Quantum Flagship program, which began in 2018.

Other disciplines must get involved to fully exploit quantum's potential. "Even if you build the heart of a quantum device, there are many layers and technologies needed to be able to work," says Folman. But materials science, engineering, chemistry, and even biomedicine have yet to team up with physics and computer science, either in Israel or worldwide. "These disciplines today do very little connected to quantum technology. It should be an interdisciplinary effort, and eventually it will be."

Shai Lev, head of business development and partnerships at the quantum algorithm design company Classiq, took on a pro bono role as cofounder of Qubit, a grassroots quantum community effort meant to attract disciplines outside of physics and computer science into the quantum world. While most of the periodic seminars the group organizes are highly technical, some are also devoted to the financial aspects of starting a business. Shir Peri Lichtig, a product operations manager at Solutio and another Qubit co-organizer, says the sessions soared in popularity and became international after the pandemic forced

them into virtual mode. Since then, such quantum oracles as Terry Rudolph from Imperial College London; John Martinis from University of California, Santa Barbara; and Chad Rigetti, CEO of Rigetti Computing, have contributed talks.

Paradoxically, another reason for Israel's big presence in tech may be its tiny size. "The maximum distance between universities here is like 200 kilometers," says Lev. "People know each other, and people are always looking for the next thing, and around them you have a vibrant community."

David Kramer

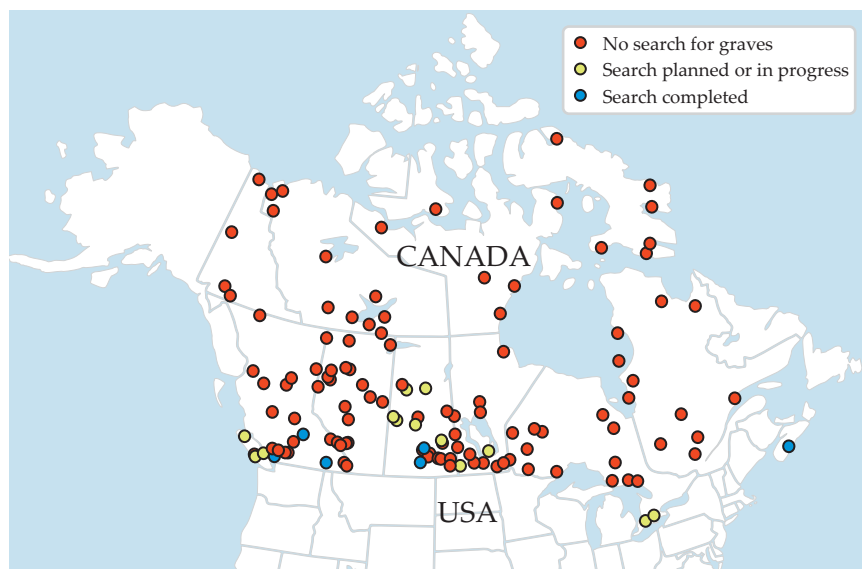
Subsurface imaging shows scale of the tragedy of Indigenous children

Archaeologists and geophysicists in Canada are trying to pinpoint the signatures of unmarked burials by using geophysical methods in varied terrains.

Few applications of radar pulses to locate objects underground have been as emotionally laden as identifying the graves of Indigenous children in Canada. The more than 200 burials located at the former Kamloops Indian Residential School in southwest British Columbia drew worldwide attention this past summer.

As part of the national government's attempt to assimilate Indigenous children into the dominant colonial culture, children as young as six years of age were forcibly taken from their families and sent to that school and many others across the country (see map) that were operated primarily by the Roman Catholic Church between 1890 and 1969. The US government enacted similar acculturation policies at American Indian Residential Schools in the same decades. Many children never returned home.

Ground-penetrating radar (GPR) has been used for several decades in engineering, geoforensics, and archaeology. (See *PHYSICS TODAY*, March 2014, page 24.) The Kamloops finding has forged a new interdisciplinary partnership to search throughout North America for other child



ARCHAEOLOGICAL SURVEYS that rely on ground-penetrating radar have identified unmarked children's graves at several former residential schools for Indigenous children in Canada. (Adapted from data from the National Centre for Truth and Reconciliation, University of Manitoba, Winnipeg, Canada.)

burial locations without disturbing them. Kisha Supernant, a Métis Indigenous woman and an archaeologist at the University of Alberta, uses maps and spatial data to explore how people in the past interacted with landscapes—for example, comparing the winter mobility patterns of different groups. Liam Wadsworth joined her research group in 2018 as a graduate student. He brought a geophysics background, training in GPR techniques, and a strong motivation to help Indigenous communities find unmarked graves. "Our goal is to make it

possible for descendants to appropriately mourn the loss of their ancestral children," says Supernant.

Hyperbolic hints

In GPR technology, an antenna transmits high-frequency radio pulses into the ground and records the return signal and the round-trip travel time. Travel times are sensitive to subsurface discontinuities that reflect, refract, or otherwise scatter the signal. Continuous profiles of subsurface reflections, called radargrams, provide an image of those discontinuities

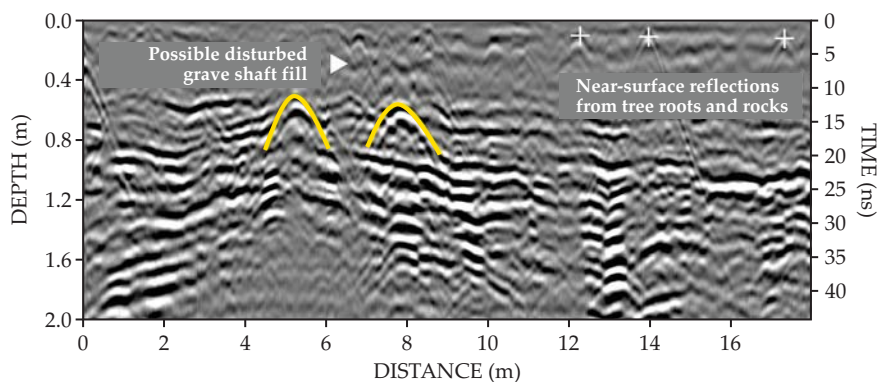
as the antennas are moved along the ground surface on lawnmower-like carts. A change in the return time of the transmitted radio waves could indicate an object, a gap, or a variation in ground composition. GPR today serves as a workhorse for mapping near-surface geological anomalies and buried utilities.

In a 1986 paper originally presented at an annual meeting of the Society of Exploration Geophysicists, Chris Vaughan discussed one of the first attempts to use GPR to search for graves. He examined a high-resolution survey of a 16th-century Basque whaling village on Canada's Labrador coast for signs of historical graves. The survey detected strong background signals that, through exhumation, were found to be associated with the burial sites. Later work by Kenneth Kvamme, an emeritus professor of anthropology at the University of Arkansas, described how that nondestructive tool could be used not just to scan individual burial sites but also to map spatial patterns over the many tens of hectares that characterize most archaeological excavations. That capability to map patterns was exactly what was needed to locate the many unmarked and undocumented graves of Canada's Indigenous children.

Those early results were promising, but their strictly empirical nature made it difficult to confidently apply GPR to areas where confirmatory exhumation was infeasible or culturally prohibited. In 2004 Lawrence Conyers, an anthropologist at the University of Denver, unraveled much of the physics behind the strong signal associated with graves. He developed methods that use the size, shape, and depth of the return signal to identify coffins and the associated vertical shaft features.

In addition to the depth of burials, important features for GPR are soil conditions, particularly the amount of clay that can attenuate the GPR wave, and the age of the grave. Older graves may hold remains in advanced stages of decomposition. The decomposed matter may make the distinction between the grave itself and the surrounding soil conditions difficult to discern.

Conyers found that GPR surveys using signals in the range of 300–500 MHz produce a good balance between penetration depth and resolution, both of which are needed to identify graves. In particular, he found that the disturbed



CONTINUOUS PROFILES of subsurface reflections, called radargrams, reveal subsurface features at the Cowper Lake Burial Ground on traditional territory of the Chipewyan Prairie First Nation, a designated group of Indigenous peoples in Alberta, Canada. The yellow curves indicate the characteristic “upside-down U” features that result from wooden coffin or shroud burials. The disturbed soil above those reflections may represent grave shafts. Surface reflections from roots and rocks illustrate the complexity of interpreting a ground-penetrating radar profile. (Adapted from W. T. D. Wadsworth et al., *Adv. Archaeol. Pract.* **9**, 202, 2021.)

soil of a narrow grave shaft creates a distinctive “upside-down U” anomaly in the return signal. The radar pulse reflects off the discontinuity at the top of the coffin or the bottom of a hollowed-out chamber. Steep-sided pits concentrate the reflected waves above them, creating the characteristic convex shape (see the image above). “If you get a hyperbola with a wave reverberating beneath it in a graveyard, there’s hardly any explanation besides a grave,” says Alastair Ruffell, a geophysicist at Queen’s University Belfast who specializes in GPR for forensic research.

A disturbing problem

In 2012 the University of Manitoba’s Katherine Nichols, then writing her master’s thesis in forensic anthropology, heard a rumor that the list of 11 students on a cemetery marker near the Brandon Indian Residential School in southwestern Manitoba was incomplete. She combed through archived death records and identified the names of 70 additional children who had disappeared during the school’s active years. Then, in collaboration with the Sioux Valley Dakota Nation—a designated group of Indigenous peoples—she conducted a GPR site survey. The results suggested there were 104 potential graves in three locations.

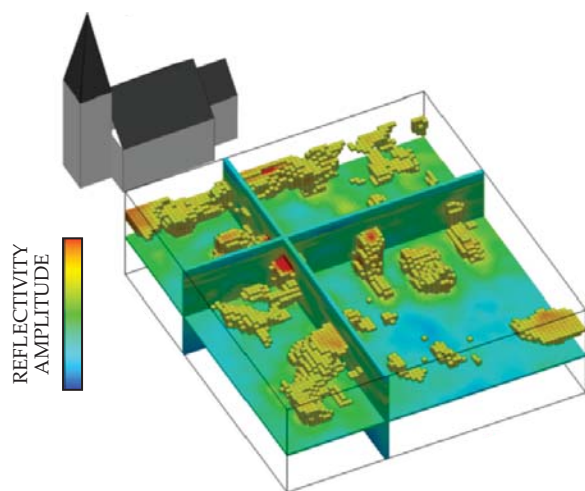
Later, in 2018, the Muskowekwan First Nation—another designated group in Saskatchewan—asked Terence Clark, an archaeologist with the University of Saskatchewan, for help locating the

remains of 35 children who were unaccounted for in school records. A team led by Clark, and including Supernant and Wadsworth, conducted surveys over three large swaths identified by Muskowekwan elders as potential burial sites. The researchers confirmed 10–15 burial sites, which the Muskowekwan First Nation now intends to mark and commemorate.

The Canadian government’s Truth and Reconciliation Commission, established in 2008 to document the history and impacts of the residential school system, suspects that there are 139 residential schools across the country with unmarked child burial sites. The potential sites range from coastal wetlands to interior forests and northern permafrost. The subsurface diversity complicates the interpretation of the GPR return signals.

Different terrains have vastly different reflectivity and noisy backgrounds. Picking out a clear, anomalous pattern from a busy background may be challenging, particularly for the small-sized burial of a child. Andrew Martindale, an archaeologist at the University of British Columbia, notes that “anthropologists and archaeologists have been enthusiastic about using GPR, but we’ve not yet brought sufficient scrutiny to knowing what qualities of the electromagnetic signal correlate with a grave.”

Typically, 20th-century cemeteries have a uniform landscape, and graves are dug in loose, homogenous soil with consistent dimensions and spacing. That



THREE-DIMENSIONAL RENDERING of ground-penetrating radar data shows the shape, size, and depth of subsurface buried objects. Some of those objects likely correspond to unmarked burial sites at the Church of the Holy Spirit near Halifax, Nova Scotia, Canada. (Adapted from T. B. Kelly et al., *Forensic Sci. Int.* **325**, 110882, 2021.)

regularity provides a standardized signal for pinpointing unmarked burials. But the early graveyard studies from the 1980s were not generally useful for evaluating precisely how terrain variability affected the return signal that defines a grave. For example, radargrams could not be used to explore how return signals changed with the natural variability from soil types, hydration, and compaction. "There are around 23 variables that people identify as being related to a GPR burial identification, but they depend on the landscape," says Martindale. He notes that the return signal can vary significantly as a result of those variables and many other near-surface features.

Martindale's team searches for suspected graves in forested and riverine terrains and other locations unusual for cemeteries. The researchers also study how the return signal changes as a function of season due, for example, to the local water-table depth. One of their findings is that disturbing and then reburying soil—as is done during a burial—results in increased water retention, which in turn produces a subtle signal that can identify a break in the ground's soil and rock layers and the base of a grave shaft.

Martindale's basic analysis tools include a set of radargrams for each grave site that consists of virtual slices through the ground, spaced 25 cm apart. His goal is to systematically compile data with that high level of resolution to identify which qualities of the GPR signal are most indicative of a burial.

Refinements in data processing also help to improve the confidence and utility of GPR for identifying graves. For example, petroleum geoscientist Grant

Wach and his doctoral student Trevor Kelly of Dalhousie University produce three-dimensional models of underground signal anomalies that indicate unmarked burial sites (see the image above). And on the horizon for GPR is increased use of aerial imagery that can monitor terrains difficult to access on foot. Conducting an aerial search in 2017, UK authorities in northern England found the body of a child murdered in 2004 in the area they suspected the victim to have been buried; the ground was marshy and had glacial deposits overlaid with peat.

Community involvement

The residential school tragedy was officially remembered in the summer of 2021 with flags lowered to half-mast and memorials consisting of children's shoes and toys that dotted Canada's parks and plazas. Orange flags strung across fences and windows in communities across Canada reminded passersby to recall that "every child matters."

Indigenous communities now want to create grave markers and memorials that tell the bereaved families' stories. Some are calling for law enforcement to pursue criminal prosecutions. Because many of the communities want to do the investigative work themselves, Wadsworth and his colleagues have begun offering training sessions on the use of GPR systems. Taking pride in the work he and others have done, he notes, "Even grandmothers are coming and wanting to learn about GPR systems. But we know they're not coming for the technology itself. They're coming to learn about their past and move to the future."

Rachel Berkowitz 



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