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Seismic shothole drillers' lithostratigraphic logs: Unearthing a wealth of regional geoscience information in northwestern Canada

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ABSTRACT

Seismic shothole drillers' logs, record the near-surface (avg. 18.6 m deep) lithostratigraphy encountered when drilling holes to place explosive charges. These records offer a largely unrecognized wealth of geoscience information in areas for which little may be otherwise known. Stored in the Basic Files archives of petroleum exploration and seismic acquisition companies, this study first convinced companies of the potential utility of this data, then recovered the hard copy and digitally scanned records (paper, fiche, microfilm) and rendered these into a digital database and GIS. The final database of 343,989 records provides the largest source of geoscience information of its kind in northwestern Canada, and in many cases contains unique and original records on a host of subjects including surficial-, bedrock-, and hydro-geology, permafrost, and geohazards. The drillers' log records have further been used to create geospatial models of drift, till, muskeg, massive ice and ground ice thicknesses, and continue to be applied to new avenues of research such as temporal variations of bottomfast ice extents in offshore shallow marine environments. Published in freely downloadable Geological Survey of Canada Open File reports and providing commonly used database and GIS file formats, this data rescue exercise preserves and greatly enhances what was becoming an increasingly discarded corporate data set of unrecognized potential.

1. Introduction

Petroleum exploration and development, particularly in frontier northern basins of Canada, United States of America (Alaska), and Russia, occurs in terrain for which there is often scant baseline regional geoscience information on near-surface (<20 m depth) earth materials and conditions. For this reason, any data that can significantly increase the state of geoscience knowledge is likely to be deemed highly beneficial to scientific inquiry, and issues of infrastructure design, development, risk assessment and mitigation, environmental assessment and regulatory review. With this in mind, it is perhaps serendipitous that the very activity of petroleum exploration seismic reflection surveys for which shotholes are drilled to place explosive charges, has yielded a formally unrecognized wealth of baseline geoscience data [25,27–29]. This study details how historical archives of seismic shothole drillers' lithostratigraphic logs from Canada's Northwest Territories (NWT) and Yukon have been digitally rendered into database and Geographic Information System (GIS) formats, such that they now provide an unparalleled level of local and regional insight into such diverse subjects as surficial and bedrock geology, permafrost, geohazards, granular aggregate resources and muskeg thickness [31,32,36,34,35].

The example of data rescue presented in this paper is not simply a case of identifying, preserving, and making a largely unrecognized geoscience information resource publically available. It equally draws attention to the notion that large archives of geoscience data can sometimes only, or best be made sense of when integrated into a digital database and spatial format, such as provided by a GIS.

2. Seismic shothole drillers' logs

Seismic reflection surveys that utilize explosive charges require the drilling of shotholes (generally 10–40 m deep), during which, as a course of practice in Canada, drill operators log the materials being drilled through. These lithostratigraphic (a.k.a. drillers') logs variously describe the thickness, sedimentology, composition, colour, and other distinguishing characteristics of unconsolidated and bedrock materials encountered. Shothole drillers are not trained to employ formal stratigraphic techniques and nomenclature, and thus material is logged at varying degrees of resolution and accuracy. Field-based transcription of logs vary in character widely,

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and range from individual hand-written cards, to more refined pick-list and annotated stratigraphic column figures (Fig. 1). Types of lithostratigraphic information reported include characterizations of unconsolidated sediments (e.g., muskeg, clay, sand, boulders), bedrock (e.g., shale, sandstone, coal), and sundry descriptors (e.g., wet, ice, cemented). In some ways the drillers' propensity for detailing conditions that were "difficult" (e.g., gravel and sand deposits which can collapse holes, or boulders below surface), "unusual" (e.g., flowing holes, fugitive gas seeps), or that slowed drilling progress (e.g., gravel, ice, hard bedrock), makes these records potentially more useful than might be originally conceived, as such characteristics may have important geological, developmental, and hazard considerations. This was found to be particularly the case with permafrost geology. Massive ice deposits were often reported as being difficult to drill through (reflecting an absence of grit to propagate the cutting), and thus drillers tended to acutely note the presence and thickness of these. Similarly, the practice in some areas of flooding holes to freeze in explosive charges (allowing for a better transmission of percussive energy downward, as opposed to upward out of the shothole (i.e., a blowout)), led to widespread identification of frozen vs unfrozen subsurface conditions, and even the depths at which changes in thermal state occurred [36].

Prior to efforts undertaken by the author, only a few published studies, of generally limited scope, have attempted to use drillers' logs in near-surface geoscience studies [18–20,24,3,1,4,2]. There appears to have been a prevailing attitude, particularly within industry, that the drillers' logs were "junk" data, and this led to their discard from many corporate archives, and a progressive decrease in their reporting detail, if indeed they have been recorded at all during recent seismic exploration. While any individual drillers' log may be of uncertain value and reliability, when integrated with other records using GIS technologies, regional and laterally continuous data trends may be deciphered [25,29]. Further, by contrasting drillers' log data from intersecting or adjacent seismic lines, and correlating these with other geographically coincident lithostratigraphic records (e.g., Janicki's [13] formation top petroleum well database, and Smith et al.'s [37] Mackenzie borehole geotechnical database), and with regional surficial geology maps (e.g., [6,35]; see Section 3.1), it may be possible to increase interpretive confidence in the shothole data. Recent application of drillers' log data in the southern and central Mackenzie corridor, NWT, Canada, by Geological Survey of Canada (GSC) surficial geology mappers Duk-Rodkin and Huntley (pers. comm., 2010) has demonstrated their good agreement with field-based hand-dug and augered pits (1–3 m deep) and very rare, stratigraphic exposures. This has led to the extensive use of drillers' log data to help broadly define terrain units and focus field investigations on unusual deposits, and lateral changes in surficial materials.

2.1. Archival records

Earlier attempts to use drillers' log data (cf., [18,4]) were unknown to the author when a collection of 76,000 hand-written and typed file cards was discovered in the GSC Calgary office archives in 2006. Based on prior experience using seismic shothole drillers' log data to identify a buried gravel deposit in northeastern British Columbia, Canada [16,2,26], the author envisaged a similar potential for this file card archive. The file card records had been collected in 1974–1975 by Owen Hughes (GSC) as a means of supporting stereo aerial photograph-based surficial geology mapping along the proposed Mackenzie Valley gas pipeline corridor. No publication of results or accompanying metadata was found to be

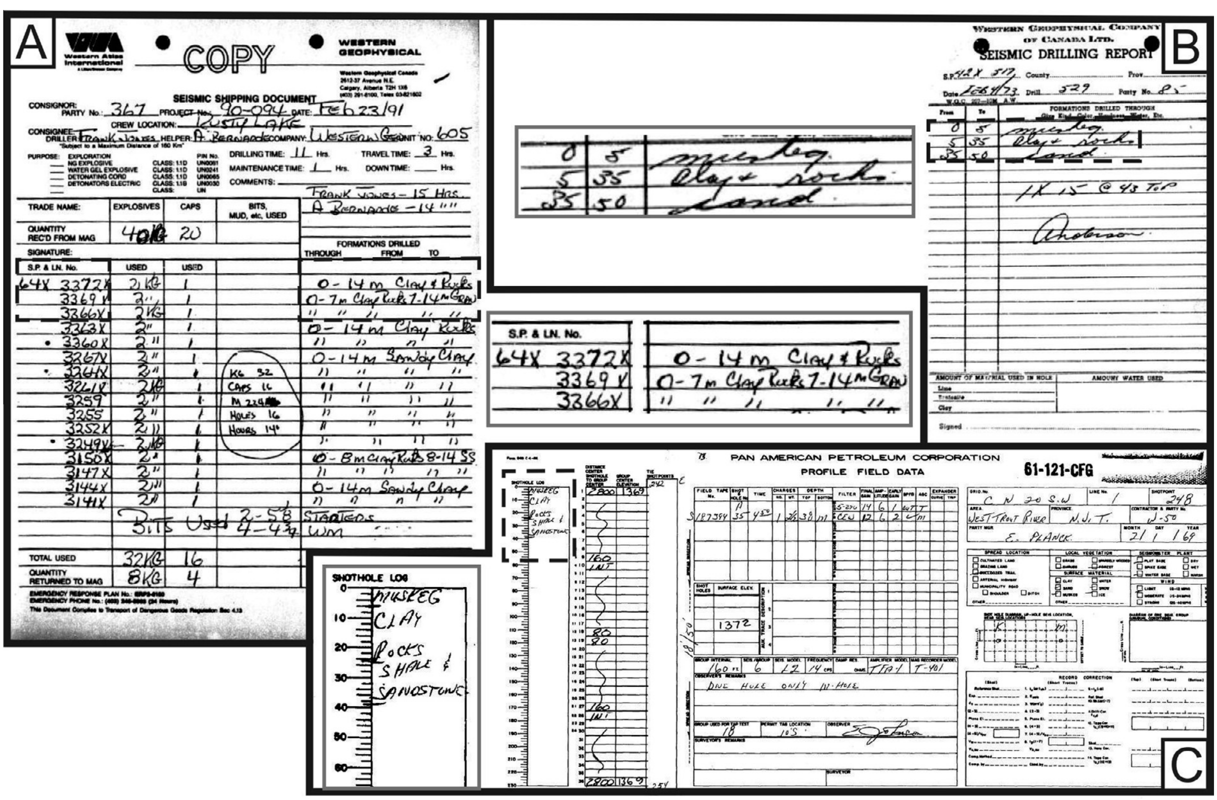

Fig. 1. Examples of 3 different Basic File records with drillers' log data; details of select lithologs have been enlarged for clarity. (A) Master Drill Sheet, seismic line 64X, shotpoints 3372X (0–14 m clay, rocks), 3369X and 3366X (0–7 m clay, rocks; 7–14 m gravel); (B) Field Drillers' Log Card, seismic line 42X, shotpoint 517 (0–5 ft muskeg; 5–35 ft clay, rocks; 35–50 sand); (C) Field Data Report, seismic line 1, shotpoint 248 (0–6 ft muskeg; 6–24 ft clay, rocks; 24–40 ft shale, sandstone; note, tick marks on scale bar indicate depths).

associated with these records. Review of the file card archive indicated that Hughes had not captured all available records from Industry. Thus, in addition to the 76,000 record file card archives of Hughes' (cf., [30]), the potential for recovering significantly more data, including all records from the post-1975 exploration period led the author to approach all existing petroleum exploration and seismic acquisition companies who had been active in the NWT and Yukon, to provide access to their archives. Eventually, all companies approached provided access to or searched their archives, and 23 companies were found to contain drillers' log records which were then contributed to the project. Permission for release of acquired and joint-venture data was also requested and received from 99 companies, successors, or data stewards. These archival records yielded 3808 seismic lines with shothole data, providing 343,989 individual shothole drillers' log records that constitute a spatially heterogeneous coverage of the two territories, reflecting both frontier exploration and detailed 3-D seismic programs (Fig. 2; [28]).

Seismic shothole drillers' log records, if retained in company archives, were typically found as part of what are classified as "Basic Files" (these included: shooters reports, observer reports, drill logs, master drill sheets, survey notes, seismic survey data, tape index sheets, layout sheets and sundry other information). Record formats included paper drill log cards, microfiche or microfilm copies thereof, paper records, photocopies, and digital scans (Fig. 1). By no means does the final shothole database [28] represent all seismic activity that has been conducted in the two territories. Because drillers' log data was previously disregarded as having any practical usefulness, it became evident during archival searches that large parts of data archives had been discarded, often following company mergers and acquisitions. While difficult to constrain (reflecting proprietary limitations to access of metadata records), it is estimated that <40% of past seismic exploration undertaken by some larger companies actually retained drillers' log records as part of their Basic Files archives. The percentage retention was generally found to be much higher with existing junior and intermediate petroleum exploration companies. An increased use of vibroseis technology has eliminated the need for drilling shotholes, so many recent seismic operations are not represented in the current database. The final shothole database [28] spans 1952–2008, and provides a detailed, though incomplete, record of several cycles of seismic exploration activity in the territories (Fig. 3).

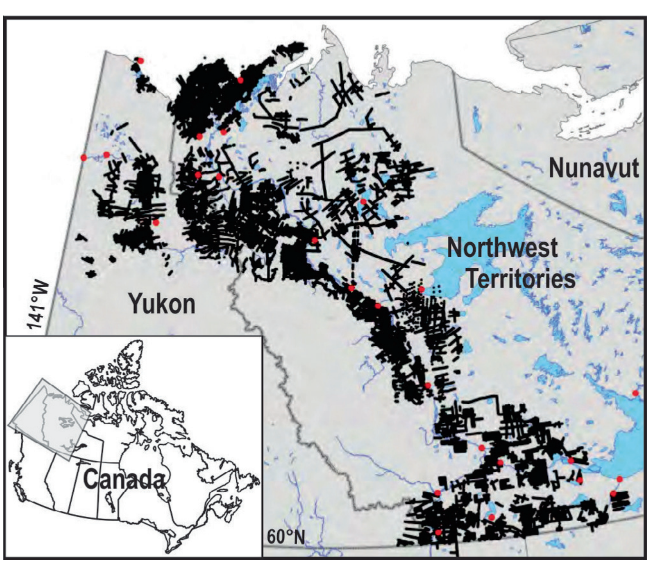

Fig. 2. Geographic extents of 343,989 seismic shothole drillers' logs (black dots and lines) in Northwest Territories and Yukon, northwest Canada. Red dots identify communities. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

As little or no use had been made of shothole drillers' log data, their preservation and clarity of reproduction was often poor, and considerable efforts were at times required to decipher what may have been extreme cold and adverse field condition-induced scrawl; any records for which the transcription of notes was uncertain were omitted. Transcription of records involved the author (who input approximately a third of all records) and many student database technicians employed for various terms over the course of 4 years, using a custom-built Microsoft® Access® data entry form (Fig. 4). Use of optical character recognition (OCR) software was untenable given the various formats, and state of records (Fig. 1). Entries of each student database technician was overseen by the author and typically reviewed by a second technician. A thorough quality-checking exercise undertaken to review the input of the original file card records and an interim version 2 shothole database (275,871 records; [33]) revealed a 0.5% error rate. The vast majority of these errors related to the omission by one student of the adjective "wet" (e.g., 0–10 m wet clay, 10–18 m gravel, ice, sand), which was subsequently corrected prior to publication of the final database [28]).

In addition to the drillers' logs, it was recognized that company, location, date and other associated metadata also provided a wealth of information. For example, it has been reported to the author that the date when the seismic line was cut has been used to study the environmental effects of clear-cutting and vegetative recolonization in NWT. Collation and publication of this and other seismic exploration metadata also serves as the only public archive of this information, and may well be the only source of such information for the pre-mid to late 1970s when the National Energy Board (NEB) of Canada began collecting seismic exploration reports. It should also be noted that the NEB archives typically do not contain much of the Basic Files materials, and a search of their records by the author yielded none with drillers' logs.

2.2. Data and litholog characterization

All shothole drillers' lithologs were originally transcribed exactly as they were written. This yielded >16,000 unique permutations and combinations of log material descriptions. By standardizing slang, terminology, spelling, punctuation, and removing vague and/or extraneous descriptors (e.g., hard, soft, heavy, shattered, etc.), the list was reduced to 5144 unique lithologs, 44.5% of which are cited only once, 79.1% of which are cited ⩽10 times, and 94.9% of which are cited ⩽100 times (cf., Table 1 in Smith [28]). Most lithologs pertain to permutations and combinations of <20 key terms. Descriptors of unconsolidated materials include muskeg, clay, silt, sand, gravel, rocks, boulders and till; bedrock descriptors include shale, sandstone, limestone, dolomite, coal, granite, rock, and bedrock; sundry descriptors and adjectives include wet, water, flowing hole, flowing sand, frozen, permafrost, ice, gas, sticky, cemented, and various colours. Combinations of particular lithologies were not translated into more formally recognized sedimentological and morphogenic terminology (e.g., clay, sand, rocks = till; cf. [39]), although for the most recent thematic publication [35], this was undertaken as a test of existing surficial geology mapping in the Tuktoyaktuk Peninsula, NWT region. Differences in the types of information recorded were noted between drillers working on the same seismic program, and between different programs. Also, units such as sand/frozen sand and sandstone, and clay/frozen clay and shale may have been misinterpreted in some instances, particularly where the bedrock may be poorly consolidated.

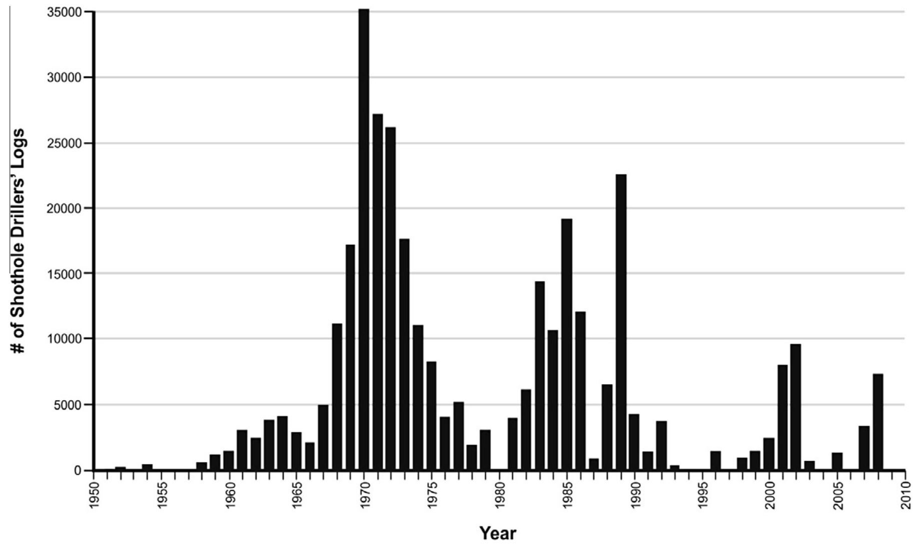

Fig. 3. Histogram of shothole drillers' logs per year in the shothole database [28]. Cycles of exploration activity reflect a number of economic, geopolitical, regulatory, and infrastructure-related drivers. Declines in shothole log numbers in the past two decades reflect, in part, a slow-down of exploration activity, and an increased use of vibroseis technologies for which shotholes are not required.

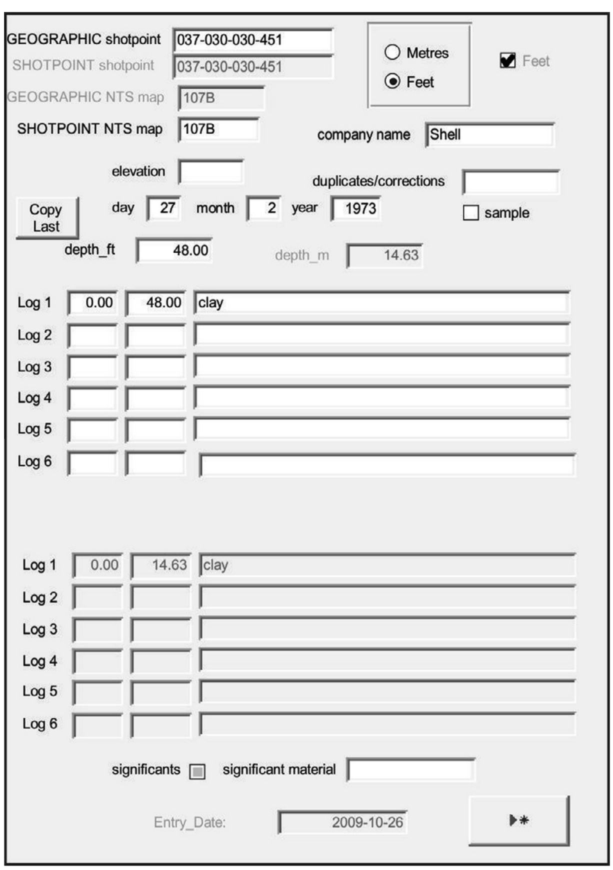

Fig. 4. Custom built Microsoft® Access® data entry form used to input archival shothole drillers' log data. Separate "Shotpoint" and "Geographic" tables were simultaneously populated from this form into which other metadata was later compiled. The Unique Identifier (UID) 037-030-030-451 identifies the company-seismic line identifier-seismic line number-shothole number. Records could be input in imperial or metric (automatically converted), and any field could be set up with default values/entries to speed input.

Drillers' logs were reported in two general formats. The majority (63.4%; [28]) recorded all materials encountered through the depth of the hole as a single litholog, of which 15.4% of these (9.8% of all shothole records) comprise only one lithological unit, one third of which are bedrock (e.g., 0–18 m sandstone), and two thirds are unconsolidated material (e.g., 0–12 m clay). In those records containing only a single lithological unit, it is a concern that the litholog simply records what was in the bottom of the shothole, rather than what was encountered throughout its depth, e.g., a hole logged as 0–18 m shale, could comprise some undetermined type and depth of material (up to 17 m thick) overlying an undetermined depth of shale (the top of which lies 0–18 m below surface). Certainly extensive areas of seismic exploration in the NWT and Yukon occurred in areas where bedrock occurs at surface, just as there are areas where shotholes would fail to penetrate a single lithostratigraphic drift unit (e.g., 0–10 m sand). Therefore, potential "errors" of reporting only the material at the base of a shothole are considered small. The other 84.6% of the single litholog records have multiple lithologies which are not stratigraphically distinguished as individual units (e.g., 0–18 m clay, ice, sand, shale). It is assumed that the order of lithologies either represents their stratigraphic position (e.g., surface clay, overlying ice which is underlain by sand and then shale), or in the case of complex drift units (e.g., 0–18 m clay, sand, rocks) it is assumed that the drillers were indicating the relative percent composition (i.e., clay was the dominant material, with lesser amounts of sand and rocks – this would be typical of till deposits). The other format that the remaining 36.6% of all drillers' logs were reported in, noted major changes in lithostratigraphy in two (e.g., 0–10 m clay, sand, rocks; 10–18 m shale; 27.1% of all drillers' logs) to seven distinct stratigraphic litholog records.

Shothole depths average 18.6 m, and range from 3 to 90 m. Individual shothole spacing was typically some multiple of 110 feet, with 330, 440 and 1430 being the most common [28].

2.3. Data and location uncertainties

Methodologies, data uncertainties, and assumptions are discussed in detail in Smith [28] and within the accompanying reports in each thematic GSC Open File publication. Caution is urged in the interpretation and application of all shothole drillers' log data, particularly as it may concern the accuracy of the records. For example, in the case of where a driller reported that a unit is frozen and contains ice lenses – it is likely that this is true. However, if similar conditions are not reported in an adjoining shothole or seismic line, this may not necessarily indicate that the material is not frozen and does not contain ice lenses – it may simply mean that the driller did not report these. In this example, it is perhaps more useful to distinguish records that indicate materials in a frozen condition, from those that demonstrably state the materials are not frozen, i.e., indicate the presence of liquid water.

Shothole location data may have the greatest absolute uncertainty. For the vast majority of records (86%; [28]), shothole locations were based on company-provided SEGP-1 files. SEGP data spans five decades of different survey technologies, from the early days of rods, chains, and star-shots to the now highly accurate differential base station GPS. Comparisons with orthorectified satellite imagery and field surveys utilizing the shothole data do not indicate great disparity in overall line location (generally <100 m off), however, individual shothole locations are not preserved on the ground, so cannot be verified. Occasionally, individual shotholes could have been drilled in positions offset (inline or perpendicular) metres to tens of metres from the original surveyed coordinates. Information on such offsets may be recorded in shooters' or observers' logs, but was not considered in the determination of shothole location (access to these metadata records was often not permitted in the archival searches and retrieval). The remaining 14% of all shothole record locations had to be digitized off of shothole survey basemaps. This was initially the case for all of Hughes' original file card archive which had hand drawn shotpoints and seismic lines on 2× enlarged mylar 1:250,000 scale topographic basemaps. About half of these initial map-based coordinates were subsequently updated with company-provided SEGP data. Differences between the two were generally within 20–350 m of each other (most were <150 m). The actual method used to generate coordinate data for each shothole is included in the database metadata table [28].

Shotpoints for which location data could not be recovered from company archives, or for which obvious disparities were identified (i.e., coordinates that plotted in a nonsensical geographic location), were omitted from the final database. There remain approximately 7400 drillers' log records for which coordinates are unknown – some of this may reflect changes/errors in seismic line numbers recorded in the field versus what exists in company archives, while others may simply reflect the corporate loss of reference material.

2.4. Publication formats and availability

Considerable thought was put into how the vast amount of point lithostratigraphic shothole data could be organized and published in publically available and interpretable formats. A Microsoft® Access® database was deemed the most practical and widely accessible vehicle for compiling the records and associated metadata. Simple and complex hierarchical queries of the database were then used to assemble thematic subsets of information. These were converted to individual shapefiles (.shp) and layer files (.lyr) which can be viewed with conventional GIS software. They were also compiled in an ArcGIS map document (.mxd) file which would automatically launch the entire GIS compilation when opened in ArcGIS. In order to provide even wider access to the spatial reconstructions by non-technical experts, an ArcGIS portable map format (.pmf) file which can be viewed using a freely downloadable version of ArcReader® was also included. Opening this .pmf document will allow users to turn on and off various layers, print copies of images, but not add additional layers or data. The shapefiles and database tables included with each thematic publication serve as models for how users may wish to construct their own queries of the shothole data. They also illustrate some of the inherent limitations of the data, and by example, show what kinds of records were included in various analyses, and which were omitted [25]. Copious documentation, including methodologies, data and metadata description and analyses is included with each GSC Open File publication in the /doc folder. All shothole-based publications are freely downloadable from Natural Resources Canada's GeoScan web site (http://geoscan.nrcan.gc.ca/geoscan-index.html).

3. Application of seismic shothole drillers' log data

The seismic shothole drillers' logs present new types of near-surface lithostratigraphic and geoscience information, and orders of magnitude more data of other types than was previously available [28]. Reconstructions and modelling based on this data include: massive ground ice and permafrost geology [27,35,36], drift and till thickness (isopach) and till facies [31], bedrock outcrop, subcrop, geohazards and muskeg thickness [32], and granular aggregate resources [34]. Examples of two of these thematic publications (granular aggregate and massive ice/ground ice) and a third new research topic (bottomfast ice) are discussed briefly below.

3.1. Granular aggregate resources

Of all the shothole drillers' log publications, those relating to granular aggregate resources [34] have seen the most immediate and widespread uptake (cf., [17]). This reflects both the economic value of the material, and the recognition that granular aggregate (e.g., sand, gravel, rocks, boulders) is critical to all manner of infrastructure development, and in Canada's northern territories, supplies are considered sparse or simply unknown [41,12].

There are 76,958 potential granular aggregate deposits identified in the shothole drillers' log records, and these are distinguished by stratigraphic position (surface: 45,683 and subsurface: 20,962), sedimentology (gravel: 21,586; gravel and sand: 18,329; sand: 26,730), and thickness (displayed in the GIS by thickness proportional symbols when viewed at scales >1:500,000; Fig. 5). There are also an additional 10,249 potential granular aggregate deposits identified as "granular aggregate present, thickness unknown" that relate to drillers' logs that identify potential deposits, but fail to stratigraphically separate them from underlying bedrock (e.g., 0–18 m gravel, sand, shale). The granular aggregate publication has also sought to integrate the point-stratigraphic shothole data with other information sources such as spatial map data, and serves as another illustration of the utility and added strength of integrating archival data into a geospatial (GIS) environment. Granular aggregate associated surficial geology deposits (e.g., glaciofluvial terraces, eskers, deltas) were extracted from existing digital surficial geology maps (e.g., [6]) and combined with the shothole data (Fig. 5). Thus, where a seismic line intersects a granular aggregate-associated map polygon, the shothole data can be used to confirm the mapper's interpretation, and can provide a basis for sedimentological characterization and volumetric determination. Shothole records indicating presence of potential granular aggregate deposits that do not coincide with aerial photograph-based mapping of surficial geology can also be used to question the map, and identify deposits that may have been missed or were too small to be individually mapped. Shothole records are also unique in their identification of subsurface deposits (cf., [16,2]) – an important consideration in areas of northern Canada where extensive surface veneers of glaciolacustrine sediment or thin till [8] may otherwise conceal economic granular aggregate deposits.

3.2. Massive ice and ground ice

Massive ice (defined as having a gravimetric water content > 250% [22] and being greater than 1 m thick [18]) and ice-rich

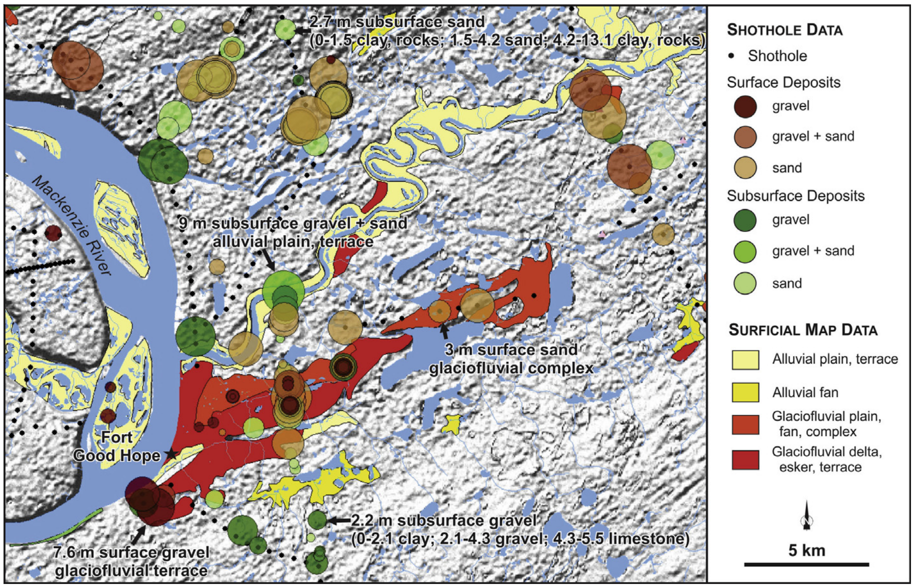

Fig. 5. Screen capture image from the GIS in Smith et al. [34] illustrating shothole-based records of surface (brown shaded circles) and subsurface (green shaded circles) potential granular aggregate deposits, and surficial geology granular aggregate associated map polygons [5]) in the Fort Good Hope, NWT area (66.26°N; 128.60°W). Size of shothole-based deposit circles is proportional to their thickness, examples of which are labelled on the figure. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

sediments (ground ice) are significant hazards encountered in permafrost regions of northern Canada. Massive ice thicknesses can exceed 60 m, and commonly underlie only a thin sediment carapace (<2 m thick; [21,35]). These permafrost terrains are amongst the most sensitive to climatic changes (cf., [15,14]). While understood in detail at specific sites, their distribution and stratigraphic context is often poorly constrained on regional bases, reflecting in large part the logistical and financial constraints on conducting permafrost field research in vast, remote northern regions.

The collection of drillers' observations of ice bodies encountered while drilling shotholes was first advocated for by Mackay in the late 1960s (C. Burn, pers. comm., 2010), after which Mackay [18] and Rampton and Mackay [24] analyzed approximately 5000 drillers' logs from Richards Island, Tuktoyaktuk Peninsula, and adjacent Beaufort–Mackenzie regions in order to reconstruct regional massive ice and ground ice characteristics. Mackay [19] expanded this study to include a reported 15,000 drillers' log records, which were subsequently compiled into a database by Côté et al. [4] (n = 13,574 records). Using both the shothole database of Smith [28] (n = 343,989 records) and the additional records from Côté et al. [4], there are now 2434 records of massive ice (e.g., 0–2 m clay, rocks; 2–10 m ice; 10–18 m sand; Fig. 6; [36]). There are also 14,049 records of what Mackay [18,19] and Côté et al. [4] classified as "icy sediments" (e.g., lithologs containing "ice" in which it is not stratigraphically separated; 0–12 m clay, sand, ice). As discussed by Mackay [18], there is a tendency for drillers to visually underestimate the ice content of sediments, and thus where they do report ice or icy sediments, it is likely that ice contents are very high. The actual distribution of massive ice may thus be better reflected by the shothole "ground ice" records, but this remains to be proven.

The sheer wealth of shothole data has provided rich new insights into massive and ground ice distribution (Fig. 6) and lithostratigraphic association – i.e., much of the massive ice in the Beaufort–Mackenzie region is considered to be "injection ice," having formed post-glacially as permafrost advected into the ground and a freezing front was fed moisture from porous materials (sand/gravel) below an overlying clay-rich till (cf., [21,27,35,36]). The shothole data also contradicts, in places, previous regional reconstructions of ground ice content [10,9]. In fairness, the shothole data is also probably the first regional source of subsurface information for much of northwestern Canada, whereas previous reconstructions were based on a small number of sites and extrapolations of surficial geology/sediment–ice associations. Further application of the shothole data could therefore be used to refine previous reconstructions, and to direct and focus detailed scientific inquiry into sites where previously unknown and/or unusual data is now indicated.

3.3. Bottomfast ice

Areas of sea ice that seasonally freeze down to the underlying sediments are referred to as bottomfast ice. In the Mackenzie Delta and coastal Beaufort Sea, bottomfast ice extents are important for controlling overland (and over-ice) flow during the spring freshet, pose hazards to offshore infrastructure such as pipelines, and influence the development of permafrost conditions in marine sediments [7,38]. Seismic lines in the Mackenzie–Beaufort region frequently extended offshore in shallow marine areas, leading drillers to document where ice was frozen to the bed, and where ice was floating (including measurements of ice thickness and water column depth; Fig. 7). Shothole bottomfast (n = 4287) and floating ice records (n = 7782) extend from the northwestern edge of the Mackenzie Delta (Shallow Bay) all the way out to the eastern tip of Tuktoyaktuk Peninsula.

Areas of bottomfast ice are indicated in the drillers' logs either stratigraphically (e.g., 0–2 m ice; 2–24 m sand, clay), or as interpreted from a compound log for a shothole situated in an offshore or lacustrine area (e.g., 0–20 m ice, sand, clay). Similarly floating ice was interpreted from records such as: 0–2 m ice, 2–6 m water, 6–20 m sand, clay; and, 0–20 m ice, water, sand. Fig. 7 illustrates all shothole-based bottomfast and floating ice records (years 1968–2000) in the outer Mackenzie Delta–Middle Channel–Niglintgak Island area. Within a GIS, individual years of record can be turned on and off, such that temporal changes in extent of the two conditions can be discerned. Note for example the area immediately north of Niglintgak Island (Fig. 7) where there are seemingly overlapping records of bottomfast and floating ice.

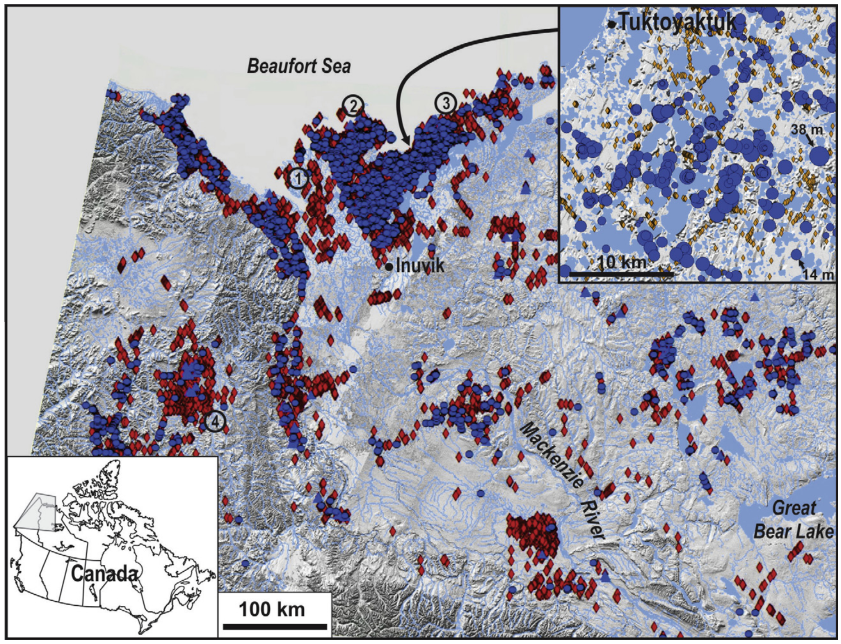

Fig. 6. Distribution of seismic shothole drillers' log records of massive ice (blue circles) and ground ice ("icy sediments;" red diamonds) in northwestern Canada. Detailed image in upper right illustrates thickness proportional blue circles of massive ice deposits up to 38 m thick southeast of Tuktoyaktuk; orange triangles represent shothole ground ice records. Numbered sites on the main figure include: 1 – Mackenzie Delta, 2 – Richards Island, 3 – Tuktoyaktuk Peninsula, 4 – Eagle Plain (Yukon). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

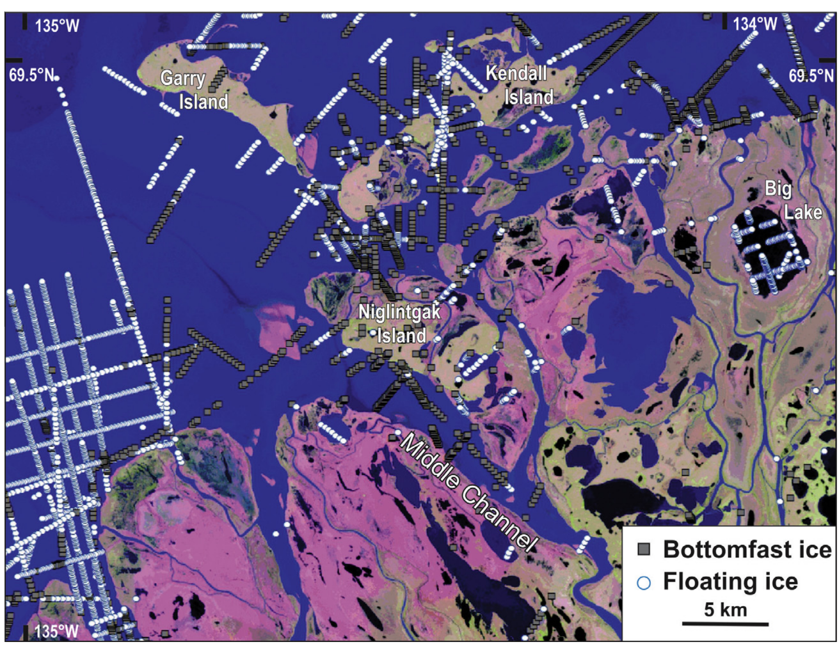

Fig. 7. LANDSAT image of the outer Mackenzie Delta–Middle Channel–Niglintgak Island area showing the distribution of shothole drillers' log-interpreted records of bottomfast ice (gray squares) and floating ice (white circles). Records span the years 1968–2000. Coastal headlands and outer Middle Channel support extensive bottomfast ice, while floating ice west of Garry Island suggests a prominent channel. Bottomfast/floating ice records also occur in lacustrine environments; notice that Big Lake is covered by floating ice, while the pond immediately to its west freezes to the bottom. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Study of individual yearly records indicates increased extents of floating ice in 1972 compared to 1975. The shothole-based bottomfast ice extents correlate well with recent field observations and remote sensing radar studies (cf., [11,38,40]). They are unique, however, in providing insights of conditions in the 1960–1970s (where most of the shothole bottomfast ice records date from), prior to any widespread study of its distribution or the advent of remote sensing detection. Also, while the Mackenzie Delta area has been the focus of field and remote sensing-based bottomfast ice research, the shothole records extend across a much larger area of the Mackenzie–Beaufort coastline (129–137° W) and therefore offer predictive power to expanded surveys and study. The added availability of shothole records in lacustrine (fresh water) basins also means that these data can be used to support reconstruction of past lake ice thicknesses. In light of the September 1999 storm surge that flooded much of the coastal area shown in Fig. 7 (pink shaded regions; cf., [23]), it may be interesting to determine if any of the freshwater ponds that formerly froze to the bottom, now that they have become saline, support a winter floating ice cover?

4. Conclusions

The seismic shothole drillers' log records provide both an opportunistic and serendipitous record of near-surface geoscience data across a vast area of northwestern Canada for which little previous knowledge existed. Despite uncertainties and limitations inherent to the drillers' log records, a cautious and considered interpretation of the data has yielded a diverse array of regional thematic reconstructions.

As a data rescue exercise, the benefits of the seismic shothole drillers' log study are considered many fold:

1. The digital rendering of Hughes' file card archive and the paper/fiche/microfilm archival holdings from Industry preserves and enhances the integrity of the drillers' log data, thereby broadening their range of potential applications.
2. An "extent of knowledge" database is created that will encourage the submission and integration of future shallow-stratigraphic and geotechnical seismic shothole drillers' log data; these data had previously routinely been discarded by Industry, and in the absence of proof of its intrinsic value, risked the progressive loss through continued discard of archival material.
3. The shothole database creates a synthesis that provides regional characterizations of lithostratigraphy, and integrates point data that were previously considered to have uncertain or unrecognized value.
4. The drillers' log data allow for the creation of derivative thematic GIS publications that facilitate original economically, developmentally, and scientifically important reconstructions and geospatial models such as the occurrence of granular aggregate resources, massive and ground ice distributions, and temporal records of bottomfast ice extents.
5. The resulting database and GIS shapefiles could be used by Industry, Government, or regulatory bodies to better constrain, plan and budget for future geotechnical seismic operations, infrastructure development (e.g., roads, pipelines), and environmental planning by allowing users to assess information relating to the nature and thickness of surficial and bedrock materials, and identify the types of geohazards that may be encountered in an area.
6. Baseline geoscience data, which aids in the creation and review of land-use classifications and future environmental impact assessments by Industry, Government, aboriginal organizations, communities and environmental groups, is made publically available.
7. The database provides the basis for construction of predictive models and a dataset of unique sites and observations that will and have already been used by geoscientists to constrain and guide future field investigations of surficial, bedrock, hydro and permafrost geology, sedimentology, and geohazards.

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