The Canadian Liquefaction Experiment: An Overview

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Abstract

The Canadian geotechnical engineering community has completed a major collaborative 5-year research project entitled the Canadian Liquefaction Experiment (CANLEX). The main objective of the project was to study the phenomenon of soil liquefaction, which can occur in saturated sandy soils and is characterized by a large loss of strength or stiffness resulting in substantial deformations. In many areas of Canada, large structures are constructed on or comprised of sandy soils; e.g. some major hydro-electricity earth dams and many tailings impoundments in the mining industry. The behaviour of loose sandy soils can be difficult to predict, but can have a significant financial impact on these types of engineering structures. Consequently, the intent of the CANLEX project was to improve the overall understanding of soil liquefaction. This paper provides an overview of the CANLEX project, outlining the project objectives, participants and major achievements and conclusions. Five companion papers describe different aspects of the project; thus, together, the six papers provide a complete summary of the CANLEX project.

Key words: geotechnical, liquefaction, CANLEX, collaborative project.

Introduction

The Canadian geotechnical engineering community has completed a major collaborative research project entitled the Canadian Liquefaction Experiment (CANLEX). The phenomenon of soil liquefaction can occur in saturated sandy soils and is characterized by a large loss of strength or stiffness resulting in substantial deformation. In many areas of Canada, large structures are constructed on or comprised of sandy soils. Examples of such structures are some major earth dams used for hydro-electricity and many tailings impoundments developed by the mining industry. The behaviour of loose sandy soils can be difficult to predict, but can have a significant financial impact on these types of engineering structures. The characterization of loose sandy soils is an area of uncertainty in geotechnical engineering. Unlike clay soils, it is almost impossible to obtain undisturbed samples of loose sandy soils, especially at depth, using conventional methods. Hence, in-situ testing techniques have become standard practice for sand characterization and the evaluation of liquefaction potential.

The CANLEX project has involved detailed investigation of six sites containing loose sand deposits. The sites were all located in Western Canada as shown in Figure 1. Advanced techniques of ground freezing and sampling were used to obtain undisturbed samples of sand from the six test sites for testing in the laboratory. In-situ testing was also carried out to characterize each of the six sites. Links were then made between the results of the laboratory testing and the in-situ testing in order to develop a recommended framework for liquefaction analyses at other sites in the future. This paper presents an overview of the CANLEX project. Five companion papers describe different aspects of the project (Wride et al., 1998a and 1998b;

Vaid et al., 1998; Byrne et al., 1998; Robertson et al., 1998); together, the six papers provide a complete summary of the CANLEX project.

Prior to the start of the CANLEX Project, a similar type of detailed field and laboratory investigation was carried out at Duncan Dam to characterize the sandy soil beneath the dam, as part of a dam safety review by B.C. Hydro (Little et al., 1994). Several of the CANLEX participants were involved in various aspects of this study. The results of the Duncan Dam study have been incorporated into the CANLEX project.

Project Objectives

The overall goal of the CANLEX project was to focus and coordinate Canadian geotechnical expertise on the topic of soil liquefaction. The major objectives of the CANLEX project were as follows: to develop test sites to study sand characterization; to develop and evaluate undisturbed sampling techniques; to calibrate and evaluate in-situ testing techniques; and to obtain an improved understanding of the phenomenon of soil liquefaction.

Project Organization

Participants

CANLEX was a collaborative project with participation from industry, engineering consultants, universities and other related organizations. Table 1 provides a list of all of the participants.

Collaboration

The CANLEX project has been the largest collaborative research project within the Canadian geotechnical community. In general, the collaboration has been excellent. Expertise exists in all segments of the project (i.e. industry, consultants and universities) and participants have shared ideas and comments freely and openly throughout the project.

Management Structure

The CANLEX project has operated under a two level management system with both Management and Scientific Committees. Peter Robertson of the University of Alberta was the Principal Investigator. Beat List of Syncrude Canada Ltd. was the Project Manager and assisted in the coordination and monitoring of project activities. Barbara Hofmann acted as an engineering coordinator, supervising field work at the test sites and providing assistance to the management team during the first two years of the project. Catherine Wride also acted as an engineering coordinator, compiling and analyzing the test results generated by the project.

The Scientific Committee, which was chaired by Peter Robertson, was comprised of representatives from the industrial participants, the test site owners, the engineering consultants and the universities. Les Youd, from Brigham Young University in Utah, acted as the external reviewer for the project and attended most of the Scientific Committee meetings. The Scientific Committee was responsible for the development and review of the scientific program. Recommendations were then made to the Management Committee for final approval.

The Management Committee, which was chaired by Norbert Morgenstern of the University of Alberta, was comprised of the major industrial financial contributors, one representative for all of the consulting companies, one representative for all of the universities, the Principal Investigator and the Project Manager. The Management Committee was responsible for financial approval and control as well as protocols related to reporting, publication and data distribution.

Summary of Progress

Test sites

The CANLEX project was carried out over an approximately five year period, from February 1993 to December 1997. The project was divided into five phases with each phase representing essentially a new site and/or research objective. The various phases are summarized in Table 2. Each project phase was subdivided into a series of activities, with each activity assigned an activity leader and group of participants. Both undisturbed and reconstituted laboratory testing were carried out on the three main soil types that were encountered at the test sites (Syncrude sand, Fraser River sand and Highland Valley Copper (HVC) sand).

Phases I and III were carried out at the Syncrude Canada Ltd. site located north of Fort McMurray in Alberta (see Figure 1). The Syncrude tailings sand was a product of the oil sand extraction process. The native oil sand was processed to remove the bitumen and then deposited hydraulically. As shown in Figure 2, Phase I was located in Cell 24 of the existing Mildred Lake Settling Basin, whereas Phase III was located slightly northwest of the Mildred Lake Settling Basin and consisted of freshly deposited tailings placed in an old borrow pit (J-pit).

Phase II was carried out in the Fraser River delta region near Vancouver, B.C. (see Figure 1). Two sites were selected for Phase II and consisted of natural deposits of Fraser River sand. As shown in Figure 3, one site was located near the south end of the Massey Tunnel and the other was located at B.C. Hydro's KIDD 2 Sub-station. A detailed description of the geology of the two Phase II sites is given by Monahan et al. (1995).

Phase IV was carried out at the Highland Valley Copper Mine in central British Columbia, south of Kamloops, B.C. (see Figure 1). Two sites were selected for Phase IV and consisted of tailings sand from the hard rock mining operations of Highland Valley Copper. As shown in Figure 4, one site was located in an older tailings storage facility, referred to as Highmont Dam, and the other was located in a currently used tailings storage facility, referred to as LL Dam. The two sites selected for the CANLEX project were situated on the upstream beaches of the LL and Highmont dams. The upstream beach of LL Dam is composed of uncompacted underflow tailings from two stage cycloning, whereas, the upstream beach of Highmont Dam was constructed using tailings, which were not cycloned prior to being spigotted onto the beach from a header pipe which ran along the dam crest (Biggar and Robertson, 1996).

Table 3 summarizes the general site data for each of the six CANLEX sites. Included in Table 3 are details as to the location and approximate age of each deposit, as well as the location of the target zone, depth to the groundwater table, and average target zone in-situ stresses at each site. It is interesting to note that the age of the deposits varied from as young as 2 months to as old as 4000 years. Note also, that the vertical effective stress in the target zones varied from as low as

53 kPa to as high as 495 kPa, with an average of 174 kPa. The sand deposits at most of the sites are composed primarily of quartz with small amounts of feldspar and mica. The Fraser River sand has higher contents of mica and feldspar. A detailed description of the mineralogy of the fines component is given by Wride et al. (1998a).

Site characterization activities

In order to fully characterize each of the six sites, each Phase (except Phase V) involved the following activities:

- Site selection to determine the preferred study location and target zone for detailed site characterization.
- Site characterization (drilling and in-situ testing), including standard penetration testing (SPT), cone penetration testing (CPT), seismic CPT (giving shear wave velocity measurements), self-boring pressuremeter testing (SBPMT) and geophysical logging; flat plate dilatometer (DMT) testing was carried out at some sites.
- Sampling, including ground freezing to obtain undisturbed samples, large diameter piston sampling, conventional sampling using a fixed piston thin walled sampler, Christensen double-tube sampling, and sonic (rotary-vibratory) continuous coring.
- Laboratory testing, including testing reconstituted samples as well as undisturbed samples; testing was carried out to evaluate the soil response to both undrained monotonic and cyclic loading.
- Data review to analyze and synthesize laboratory and field results for each site.

To illustrate the typical layout of the detailed site characterization at each of the CANLEX sites, Figure 5 presents the detailed site plan from the LL Dam site. Frozen samples of sand were obtained from the target zone at the centre of each of the six sites (Hofmann, 1997; Wride et al., 1998a). At each site, typically around a 5 m radius from the ground freezing location, cone penetration tests (CPT), standard penetration tests (SPT), seismic CPT giving shear wave velocity (V_s) measurements, geophysical logging, and pressuremeter testing were conducted through the target zone (Wride et al., 1998b). In addition, the following conventional sampling was performed (Wride et al., 1998a): fixed piston tube sampling at the Phase I and Phase II sites; Christensen double-tube core sampling at the Phase I site; and Laval large diameter sampling at the Phase II and Phase IV sites.

Based on the results of some of the site characterization activities, Table 4 summarizes the index properties for the sand deposits within the target zone at each of the six CANLEX sites. Included in Table 4 for each site are e_{max}, e_{min}, specific gravity (G_s), D_{50}, coefficient of uniformity (C_U), approximate fines content based on SPT samples, and grain angularity. In addition, Figure 6 presents a comparison of typical grain size distribution curves for samples from each of the six sites and Figure 7 presents copies of scanning electron microscope (SEM) photographs of in-situ frozen samples of Syncrude sand (Mildred Lake and J-pit), Fraser River sand (Kidd) and HVC sand (LL Dam). Additional technical details regarding the various sand deposits are addressed in the companion papers (Wride et al., 1998a and 1998b; Vaid et al., 1998; Byrne et al., 1998; Robertson et al., 1998).

Based on the comparison shown in Figure 6, it appears that all six sands are relatively similar, falling within a fairly narrow band of grain sizes, with fines contents less than 15% and in some cases less than 5%. The Phase III site had a larger range in fines content within the target zone than other CANLEX sites (see CPT soil classification charts in Wride et al., 1998b); the grain size distribution for the Phase III site is representative of the average conditions within the target zone. Figure 7 illustrates the differences in grain angularity between the various sands at the CANLEX sites. The two Syncrude sand samples have somewhat subrounded to subangular sand particles and there appear to be aligned clay mineral platelets present in the soil matrix, associated with the tailings sand chemistry and placement process. The Fraser River sample has subrounded sand particles since the sand was deposited naturally in the Fraser River Delta. The Highland Valley Copper sample has angular sand particles and there appear to be some aligned clay mineral platelets present in the soil matrix. Based on the results of the in-situ testing and laboratory tests on undisturbed samples, all of the sand deposits appear to be uncemented.

Phase III included the construction of a full scale embankment in an effort to simulate a flow liquefaction slide (Byrne et al., 1998). Phase V was also located at Syncrude in J-pit (the site of the Phase III embankment) and included several controlled blasting experiments in an effort to simulate earthquake loading within the loose saturated tailings sand deposit.

Project schedule

Table 5 shows a schedule of activities for the CANLEX project. A total of 12 Scientific Committee and 10 Management Committee meetings were held to guide the project during the five year period of operation.

In-kind and cash contributions

Table 6 summarizes the cash and estimated in-kind contributions, in Canadian dollars (CAD) from various organizations. Significant in-kind contributions were made by industry. Site owners made sites available and provided significant logistical support for the field work. Various participants contributed in terms of senior staff time to review data and attend meetings. In addition, both industry and consultants provided reduced rates for services such as laboratory testing and field work. Syncrude Canada Ltd. provided significant in-kind support, especially for the Phase III full scale experiment through the construction of an 8 m high compacted clay embankment. Syncrude also provide partial time release for Beat List to act as Project Manager.

Project expenditures

Table 7 provides a summary of the cash expenditures, in Canadian dollars (CAD), for each phase of the CANLEX project.

Summary of Results

Publications

To date, the results of the CANLEX project have been published in a series of 70 internal reports, 5 internal newsletters, 31 conference papers, 5 news articles, 14 previous journal publications, and 16 graduate student theses (M.Sc. and Ph.D.). Most of the approximately 16 graduate students who have worked on or been involved with the CANLEX project have found employment within industry. There are some additional graduate student theses being completed. This paper and the five companion papers describe different aspects of the project; thus, together, the six papers provide a complete summary of the CANLEX project. Four of the internal reports (an introductory report plus the summary data review reports for each pair of sites) will be available through BiTech Publishers Ltd.

Technical Achievements

In general, all of the major objectives of the project have been achieved. The following is a summary of the major technical achievements:

- A consistent set of definitions for liquefaction phenomena was developed and accepted by the participants (Robertson and Wride, 1998).
- Six test sites were located and fully characterized; each site had unique features related to grain characteristics, mineralogy, age, depth, density and variability.
- A new technique was developed and evaluated to obtain high quality undisturbed samples from discrete target zones of interest using ground freezing techniques.
- The application of the Laval large diameter piston sampler was evaluated.
- The application of high quality conventional fixed piston sampling was evaluated.
- Improvements were made to undisturbed sample handling procedures.
- In-situ testing techniques were evaluated and calibrated against undisturbed sample response.

- Two controlled thawing procedures for frozen samples were developed and evaluated to minimize disturbance and re-establish the in-situ stress conditions.
- Geophysical (gamma-gamma) logging methods were evaluated, including a new radio-isotope CPT.
- The importance of consolidating samples in the laboratory under in-situ stresses (i.e. K_0 consolidation) was identified and evaluated.
- The importance of direction of loading on the response of sand was identified and quantified.
- The importance of strain compatible analyses to evaluate ground deformations was identified and evaluated.
- Improvements were made in understanding the response of sand to different types of loading.
- Improvements were made in the understanding of the density and variability of sand deposits. Each of the six deposits that were studied had considerable variability in terms of both void ratio and relative density.
- Not all sites had sand that was saturated in-situ below the water table.

Non-technical achievements

In addition, the CANLEX project had several non-technical achievements, including improved understanding of the safety of structures involving sand deposits, enhanced communication between industrial partners, enhanced knowledge and reputation of consultants, immediate technology transfer, and optimization of national geotechnical resources.

The success of the CANLEX project was noted in 1998 when it was awarded the Association of Professional Engineers, Geologists and Geophysicists of Alberta (APEGGA) Project Achievement Award. This award recognizes "a project which demonstrates engineering, geological or geophysical skills and represents a substantial contribution to technical progress and the betterment of society".

General Comments

Based on the experience with the CANLEX project, several observations can be made related to achieving success with a major collaborative research project. First, a clear and open project management structure and frequent, well-organized meetings are a necessity. Secondly, the distribution of funds and work must be based on scientific reasons and carried out in an open process. In addition, publication protocols should be agreed upon at the beginning of the project. Finally, allowances should be made for significant time and funding required to thoroughly analyze and interpret the data.

Future Directions

The Scientific Committee identified the following tasks for further research work:

- Quantify soil variability, possibly using statistical techniques.
- Evaluate in more detail the influence of high overburden stress on the response of sand.
- Improve numerical models using case histories and centrifuge modelling.

- Further evaluate the effects on soil response of factors such as age, cementation and grain characteristics (i.e. angularity, mineralogy, grain size and distribution).
- Evaluate the influence of lack of saturation on soil response.
- Further evaluate geophysical techniques; e.g. electrical techniques, cross-hole tomography.
- Evaluate role of controlled blasting as a large in-situ test for measuring earthquake ground response.
- Investigate the effect of ground improvement on liquefaction evaluation techniques.

Summary

The Canadian geotechnical engineering community has completed a major collaborative research project entitled the Canadian Liquefaction Experiment (CANLEX) with participation from industry, engineering consultants and universities. The project involved a total expenditure of 1 690 000 CAD with approximately 2 256 000 CAD of additional in-kind contributions. The CANLEX project has achieved all of its major objectives.

The CANLEX project was carried out from February 1993 to December 1997. The project was divided into five phases, with each phase representing essentially a new site and/or research objective. Each project Phase was subdivided into a series of activities, with each activity assigned an activity leader and group of participants. The results of the CANLEX project have been published in a series of internal reports, newsletters, conference papers, news articles, journal publications and graduate students theses. Further research work has been identified and a future workshop as well as possibly an international conference are planned.

Acknowledgments

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Table 1. CANLEX project participants

Type of Organization	**Project Participants**
Industry	Syncrude Canada Ltd. Suncor Inc. B.C. Hydro Hydro Québec Kennecott Corporation, USA Highland Valley Copper
Engineering Consultants	AGRA Earth & Environmental Ltd. EBA Consultants Ltd. Golder Associates Ltd. Klohn-Crippen Consultants Ltd. Thurber Engineering Ltd.
Universities	University of Alberta University of British Columbia Université Laval Carleton University
Other	Geological Survey of Canada (GSC) B.C. Ministry of Transportation & Highways (BC MOTH) B.C. Ministry of Energy and Mines Centre for Cold Ocean Resources Engineering (C-CORE) ConeTec Investigations Ltd. Hughes InSitu Engineering Inc.

Table 2. Five phases of the CANLEX project

Phase	Test Site/Activities
I	Mildred Lake Settling Basin, Syncrude Canada Ltd. - site characterization, including in-situ testing, ground freezing & sampling, laboratory testing and data review
II	Massey Tunnel, Fraser River Delta - site characterization, including in-situ testing, ground freezing & sampling, laboratory testing and data review
	KIDD2 Sub-station, Fraser River Delta - site characterization, including in-situ testing, ground freezing & sampling, laboratory testing and data review
III	J-pit, Syncrude Canada Ltd. - site characterization, including in-situ testing, ground freezing & sampling, laboratory testing and data review - full scale experiment and numerical modelling
IV	LL Dam, Highland Valley Copper - site characterization, including in-situ testing, ground freezing & sampling, laboratory testing and data review
	Highmont Dam, Highland Valley Copper - site characterization, including in-situ testing, ground freezing & sampling, laboratory testing and data review
V	J-pit, Syncrude Canada Ltd. - blasting trials

Table 3. Summary of the target zone data for each CANLEX site

Site Data						Average In-situ Stresses‡			
Phase	Location	Site	Approximate Age at Time of Testing	Target Zone (m)	Average depth of GWT* (m)	σ'_v (kPa)	σ'_h (kPa)	p' (kPa)	q (kPa)
I	Syncrude	Mildred Lake	12 years	27 to 37	21	495	248	330	248
II	Fraser River Delta	Massey	200 years	8 to 13	1.5 †	115	58	77	58
		Kidd	4000 years	12 to 17	1.5 †	154	77	103	77
III	Syncrude	J-pit	2 months	3 to 7	0.5	53	26	35	26
IV	HVC Mine	LL Dam	5 years	6 to 10	2.1	96	48	64	48
		Highmont Dam	15 years	8 to 12	4	132	66	88	66

* Groundwater table

† Tidal fluctuations occur at the Massey and Kidd sites

‡ Based on $\gamma = 18.5\ kN/m^3$ above GWT, $\gamma = 19.5\ kN/m^3$ below GWT and $K_o = 0.5$; $p' = 1/3\ (\sigma'_{vo} + 2\ K_o\ \sigma'_{vo})$; $q = \sigma'_{vo} - K_o\ \sigma'_{vo}$

Table 4. Index properties for the six CANLEX sites

Site Data			Index Properties						
Phase	**Location**	**Site**	e_{max} *	e_{min} *	G_s †	D_{50} ‡ (mm)	C_U § (D_{60}/D_{10}) ‡	**Approximate SPT FC** ‖ **(%)**	**Angularity**
I	Syncrude	Mildred Lake	0.958	0.522	2.66	0.16	2.22 (0.20/0.09)	≈ 10	subrounded to subangular
II	Fraser River Delta	Massey	1.1	0.7	2.68	0.20	1.57 (0.22/0.14)	< 5	subrounded
		Kidd	1.1	0.7	2.72	0.20	1.78 (0.25/0.14)	< 5	subrounded
III	Syncrude	J-pit	0.986	0.461	2.62	0.17	2.50 (0.20/0.08)	≈ 15	subrounded to subangular
IV	HVC Mine	LL Dam	1.055	0.544	2.66	0.20	2.78 (0.25/0.09)	≈ 8	angular
		Highmont Dam	1.015	0.507	2.66	0.25	4.00 (0.30/0.075)	≈ 10	angular

* Maximum and minimum void ratios, determined using ASTM standards

† Specific gravity, determined using ASTM standards

‡ D_x: size of particle (mm) such that x % of the particles are smaller than this size

§ Coefficient of uniformity = D_{60}/D_{10}

‖ Approximate average fines content (% passing No. 200 sieve) in the target zone, based on limited SPT samples

Table 5. Summary of CANLEX project progress

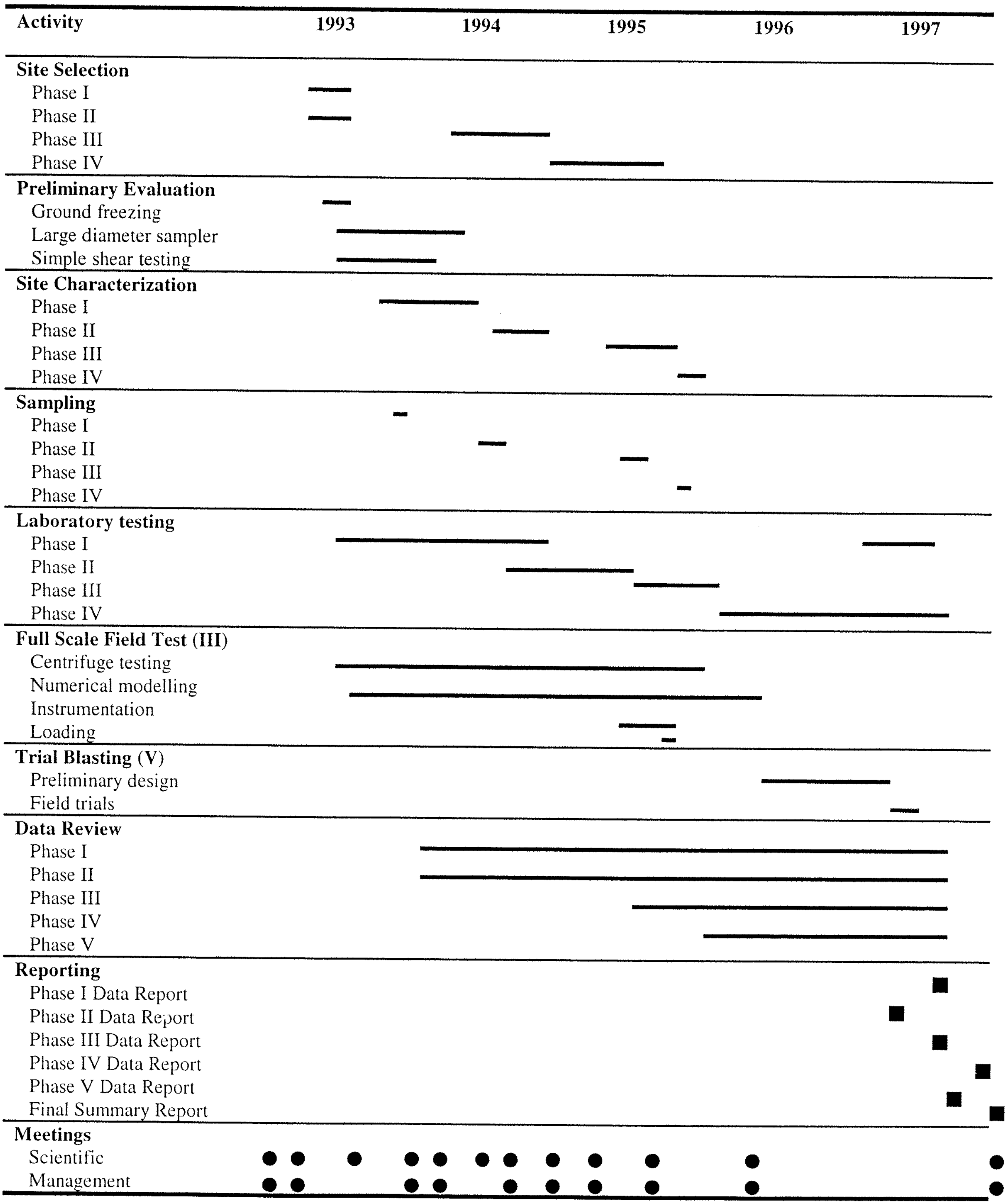

Table 6. Summary of in-kind and cash contributions to the CANLEX project

Organization	In-kind Contribution (CAD) (approximate)	Cash Contribution (CAD)
NSERC	0	1 185 000
Syncrude Canada Ltd.	1 375 000	0
Suncor Inc.	10 000	162 500
B.C. Hydro	43 000	87 500
Hydro Québec	28 000	75 000
Highland Valley Copper	50 000	137 500
Kennecott Corporation	10 000	37 500
AGRA Earth & Environmental Ltd.	22 000	0
EBA Consultants Ltd.	42 000	5 000
Golder Associates Ltd.	10 000	0
Klohn-Crippen Ltd.	32 000	0
Thurber Engineering Ltd.	18 000	0
University of Alberta	350 000	0
University of B.C.	100 000	0
Université Laval	80 000	0
Carleton University	5 000	0
B.C. MOTH	26 000	0
GSC	5 000	0
C-CORE	50 000	0
Total	**2 256 000**	**1 690 000**

Table 7. Summary of expenditures during the CANLEX project

Phase	Expenditures (CAD)
I	384 000
II	420 000
III	452 000
IV	325 000
V	60 000
Data review & reporting	49 000
Total	1 690 000

Figure 1. Map of Canada, indicating locations of the CANLEX test sites (Phases I and III near Ft. McMurray, Alberta; Phase II near Vancouver, B.C; Phase IV near Kamloops, B.C).

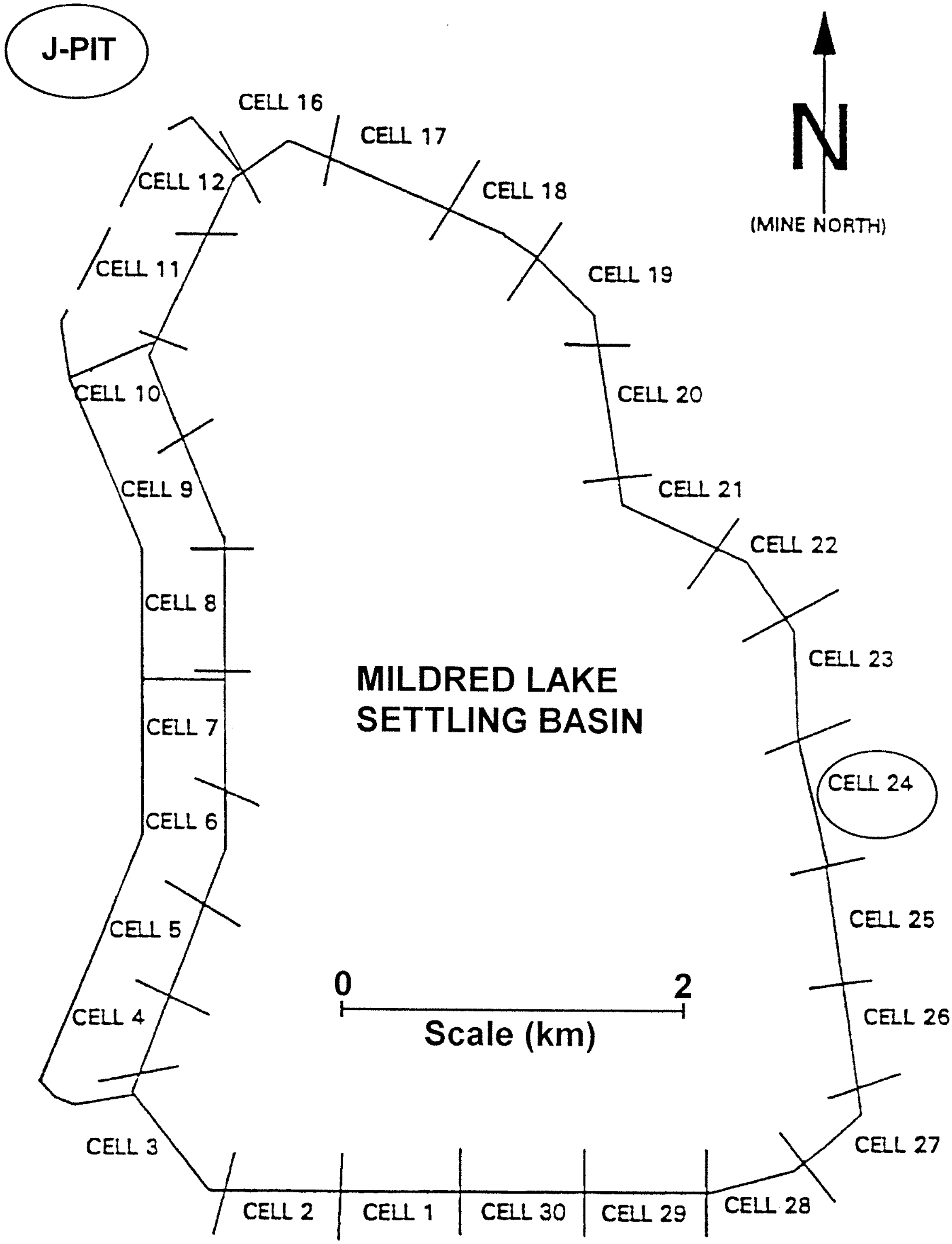

Figure 2. Phase I site, located, as indicated, in Cell 24 of Mildred Lake Settling Basin at Syncrude Canada Ltd.; also indicated is the approximate location of J-pit, the Phase III site (after Robertson et al., 1993).

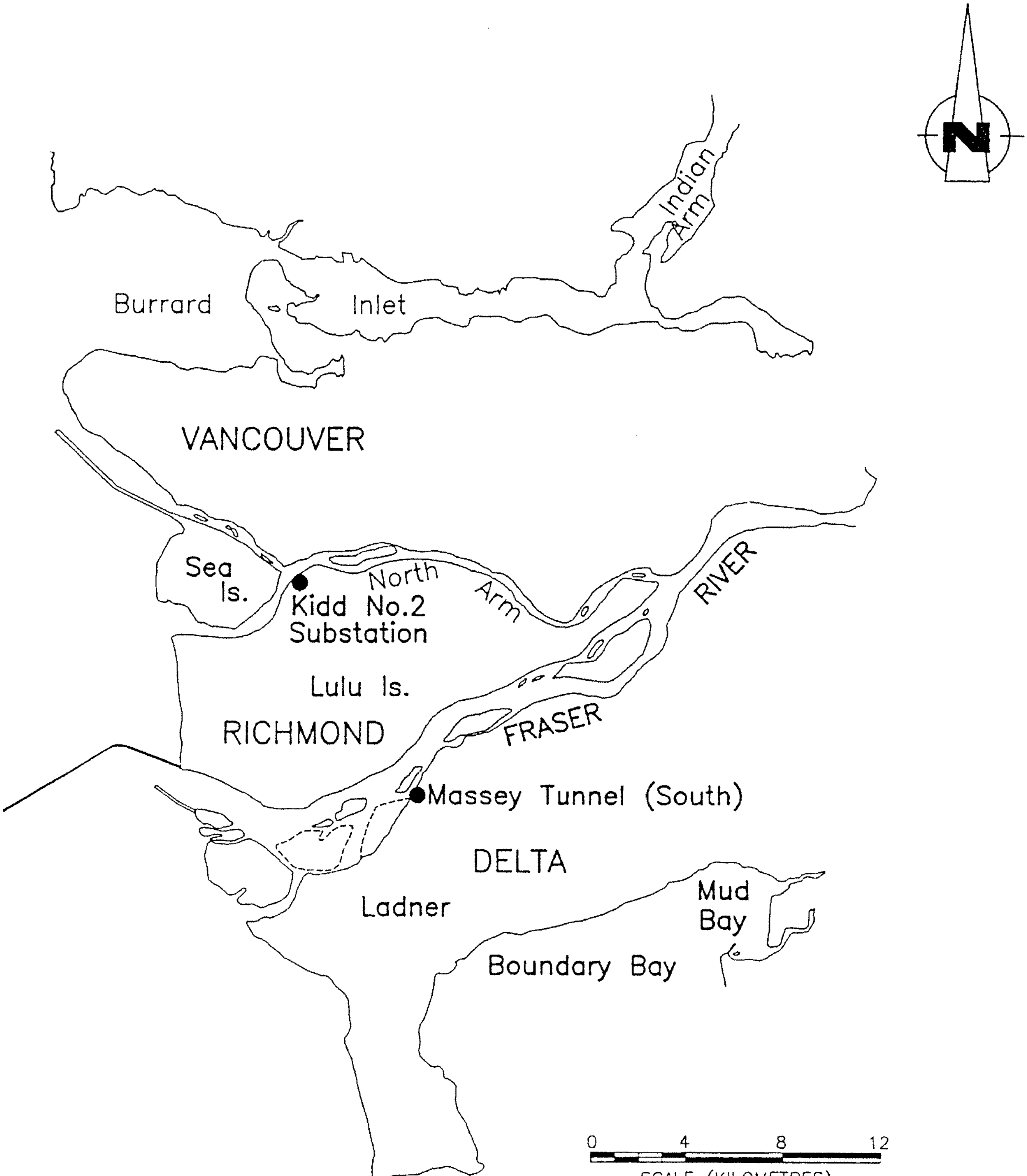

Figure 3. Locations of the Kidd and Massey sites (Phase II) in the Fraser River Delta (after Lawrence et al., 1995).

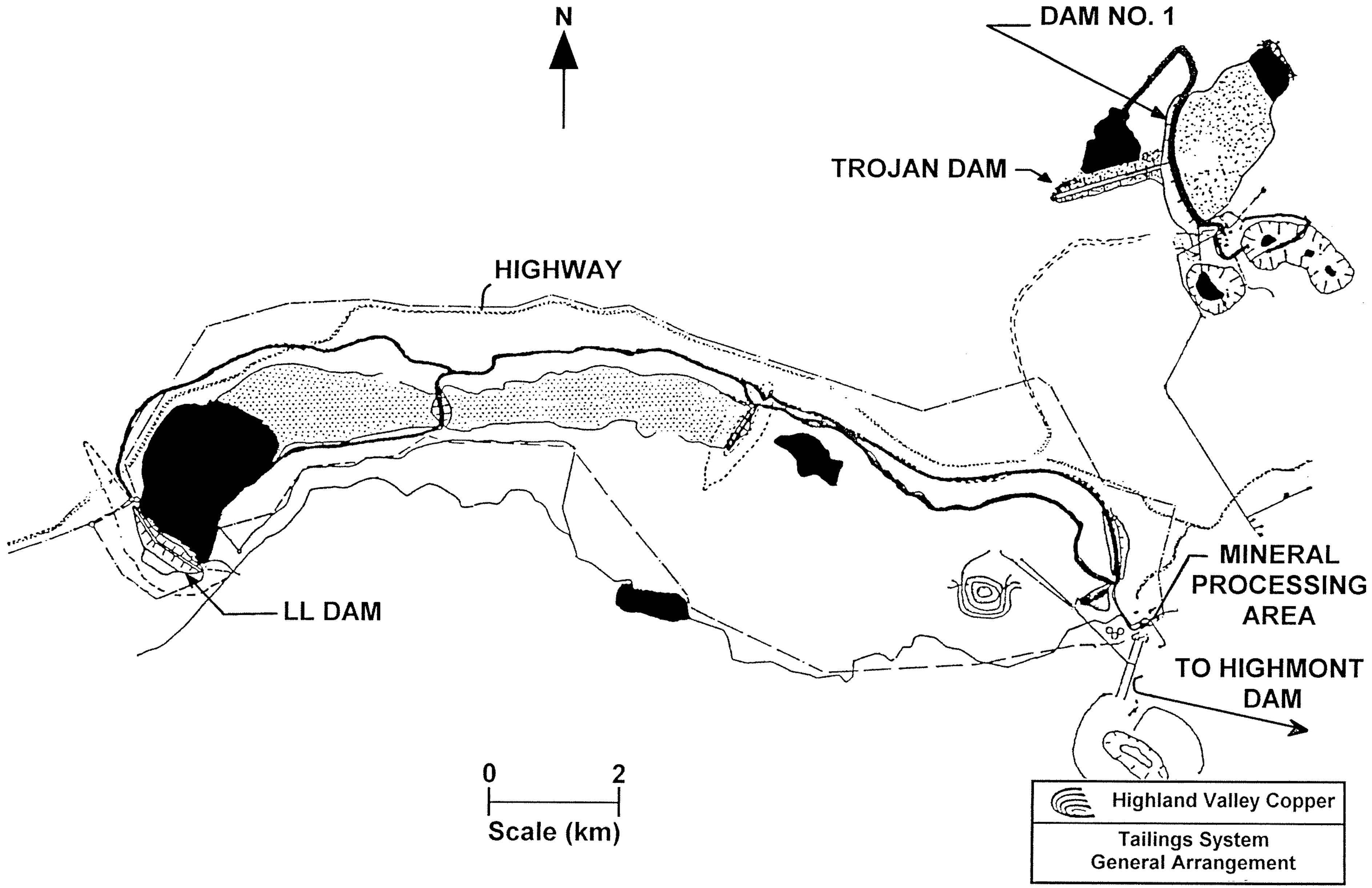

Figure 4. Mine site layout, indicating locations of LL Dam and Highmont Dam (Phase IV), at the Highland Valley Copper Mine near Logan Lake, B.C. (after Biggar and Robertson, 1995).

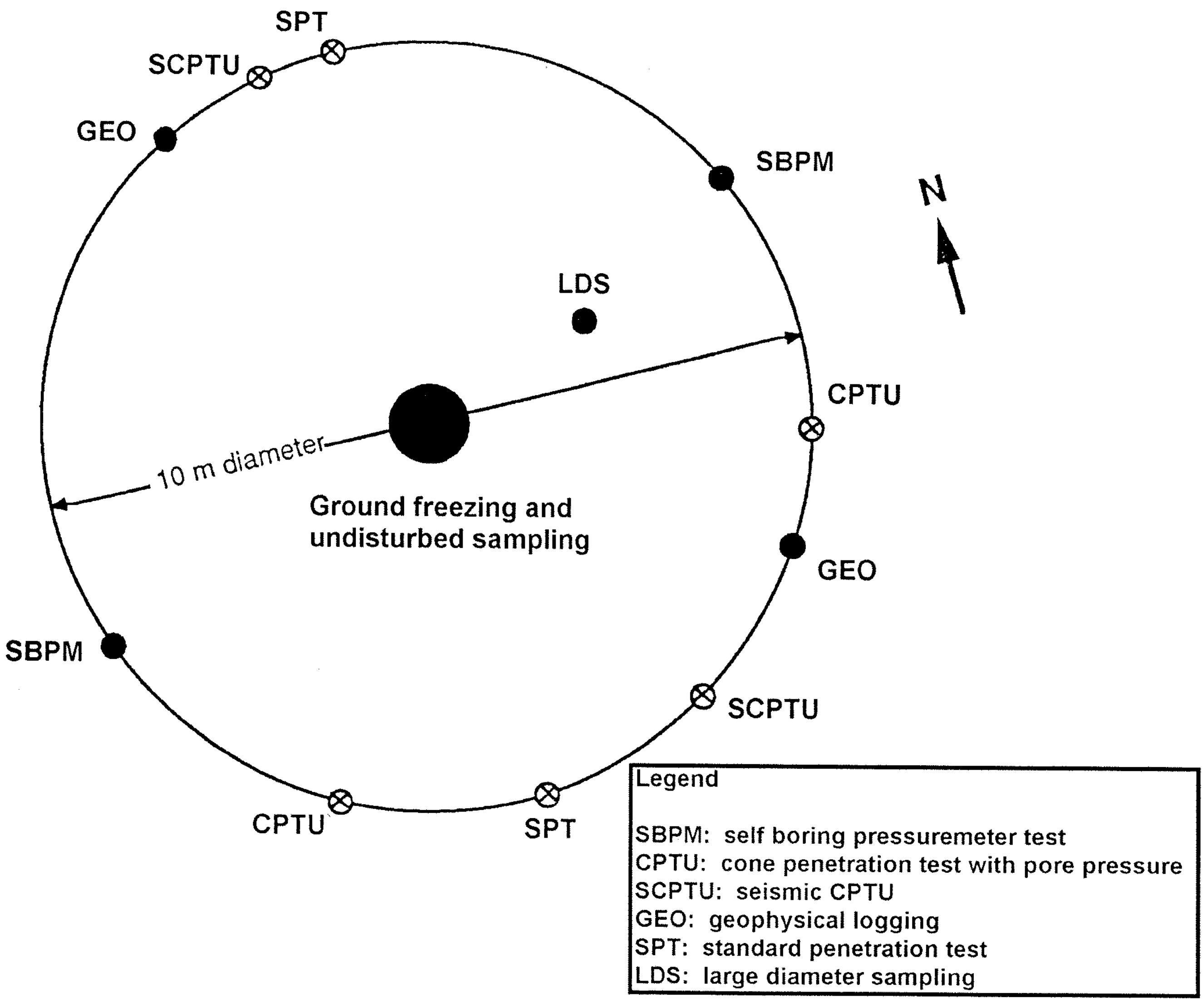

Figure 5. Typical layout of the detailed site characterization at each of the six CANLEX sites (detailed site plan of the in-situ testing area at the LL Dam site; after Biggar and Robertson, 1996).

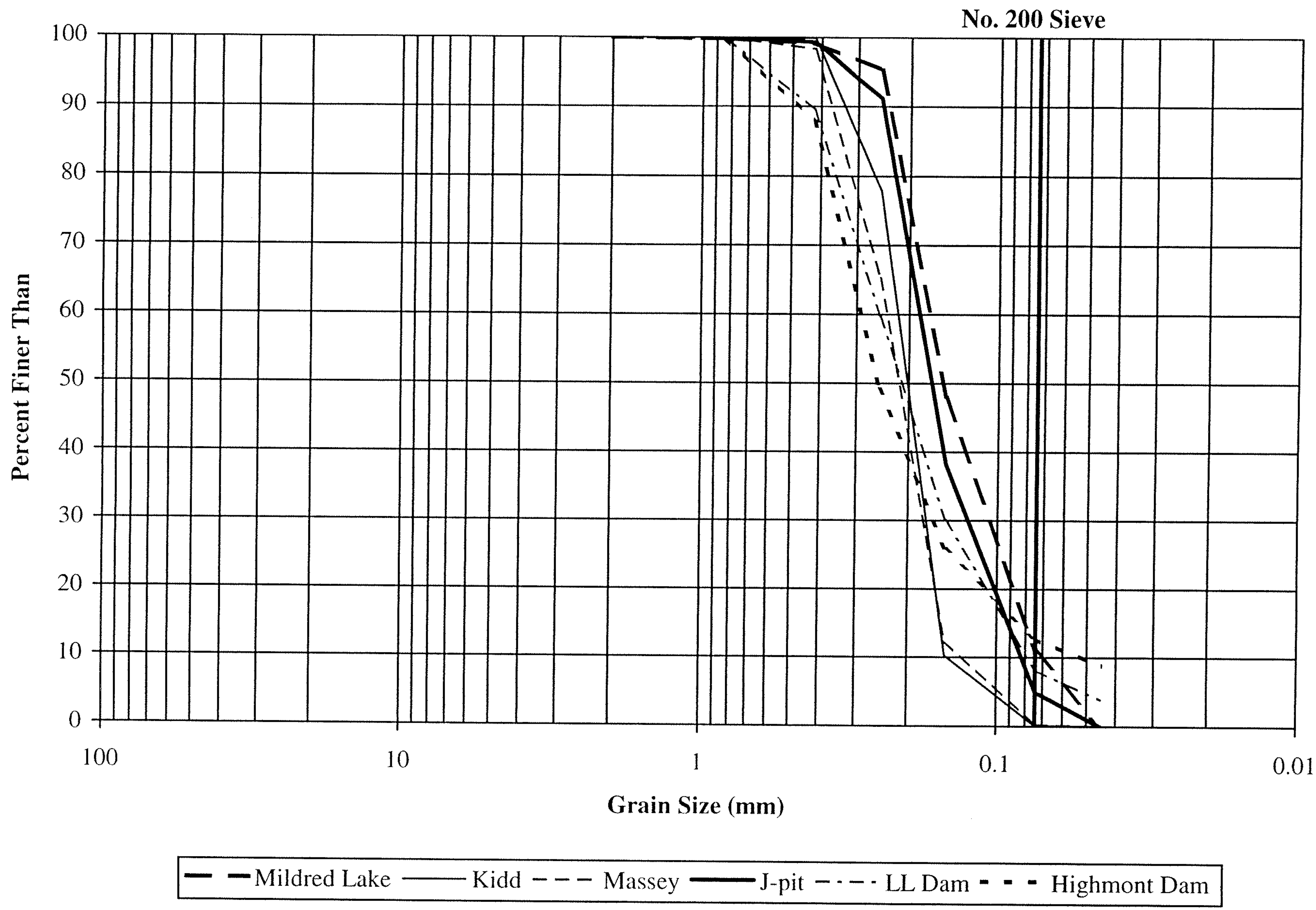

Figure 6. Comparison of typical grain size distributions for samples from each of the six CANLEX sites.

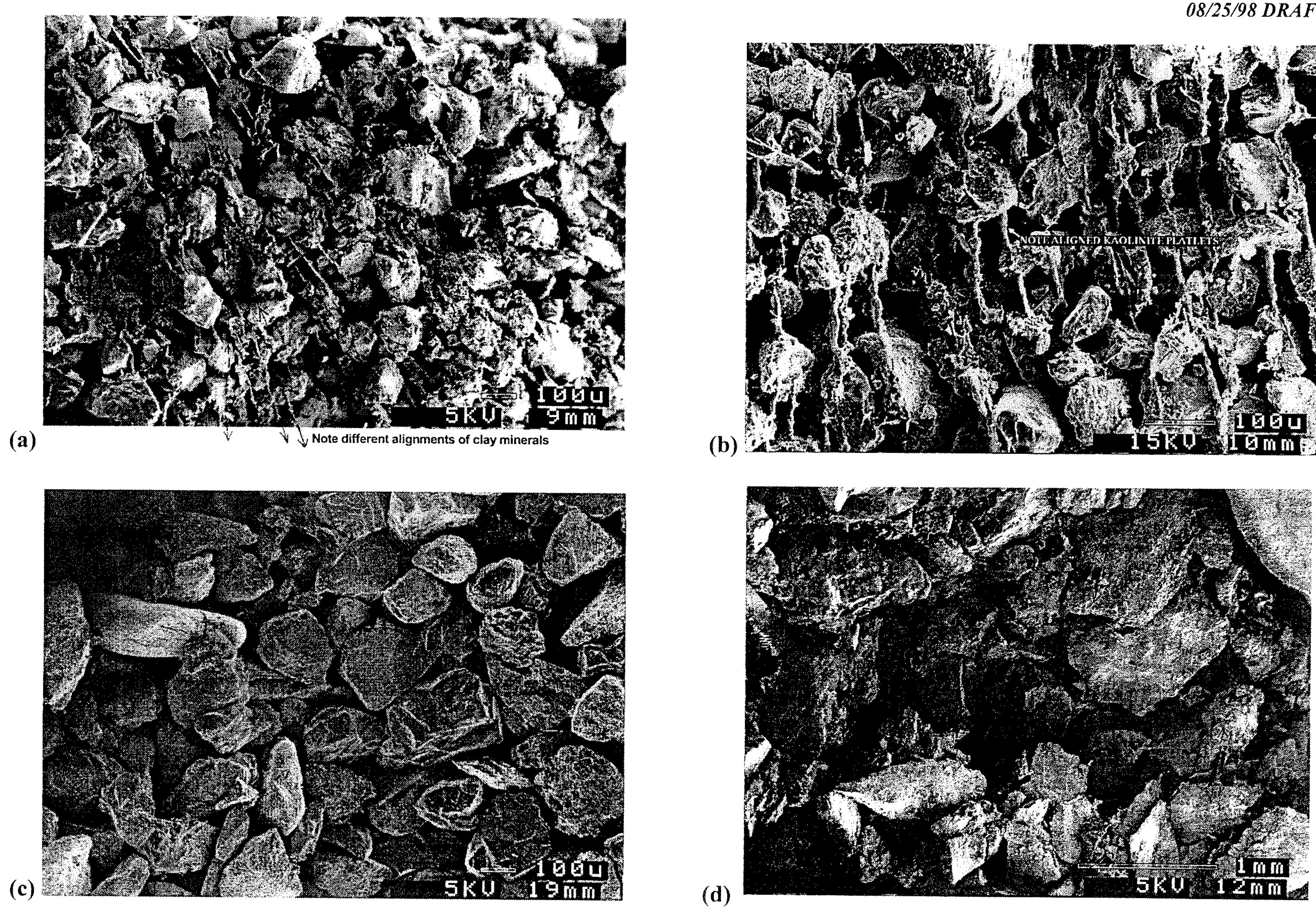

Figure 7. **Scanning electron microscope (SEM) photos of in-situ frozen sand samples from the target zones of (a) the Mildred Lake site, (b) the J-pit site, (c) the Kidd (Phase II) site, and (d) the LL Dam (Phase IV) site.**

Figure Captions

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