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Report
On
Field and Laboratory Investigations
for
PACIFIC BENTONITE LTD. NOW 218865 AND 218866
Claims Ben 1 & Ben 2, Record No. ~~8939 & 8940~~
Mineral Title Reference Map No. 92I/13E
in the
Kamloops Mining Division
Latitude 50 45N Longitude 121 35W
Annual Work Approval Number: KAM # 334956

By

Nigel A. Skermer, P.Eng.,
Consulting Engineer.

GEOLOGICAL BRANCH
ASSESSMENT REPORT

22,547

October 1992.

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ARIS SUMMARY SHEET

District Geologist, Kamloops   Off Confidential: 93.10.13

ASSESSMENT REPORT 22547   MINING DIVISION: Kamloops

PROPERTY: Ben
LOCATION: LAT 50 45 20 LONG 121 37 00
UTM 10 5623335 597578
NTS 092I13E
CLAIM(S): Ben 1-2
OPERATOR(S): Pacific Bentonite
AUTHOR(S): Skermer, N.A.
REPORT YEAR: 1992, 43 Pages
COMMODITIES
SEARCHED FOR: Bentonite
KEYWORDS: Eocene,Princeton Group,Hat Creek Formation,Coal,Bentonite
Siltstone,Claystone,Conglomerate
WORK
DONE: Drilling,Geological
ROTD 70.7 m 8 hole(s)
MINFILE: 092INW084

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Resume

1 Introduction

The BEN 1 and BEN 2 claims of **Pacific Bentonite Ltd. ("PBL")** are located on the west side of Upper Hat Creek Valley. Hat Creek is 240 kilometres northeast of Vancouver, British Columbia. The claims are reached by 25 kilometres of paved highway from Pavilion and 2 kilometres of active logging road. The paved highway is the Cache Creek/Lillooet Highway 12. The location is shown on Figure 1.

The land slopes gently to the northeast. It is semi-arid sage bush and cactus land and used mainly for cattle range. The vegetation is a mixture of open spaced pine and spruce with some meadows.

The property includes 2 four post claims BEN 1 and BEN 2 with a total of 35 units, record number ~~8939~~ 218865 and ~~8940~~ 218866, see Figure 2.

The NTS location is 92/I/13E; latitude 50 45N; longitude 121 35W.

The bentonite is a stratigraphic unit that both underlies and overlies the Hat Creek coal basin, but which is upslope above the coal in its surface exposure. It has been extensively core drilled by B.C. Hydro during the exploration for Hat Creek Thermal Project. The findings of that work indicated that the bentonite was to be removed as the open pit coal mine was developed. There are no current plans to proceed with the coal mine, however.

The bentonite is potentially a valuable commodity with uses in drilling, civil engineering and in a variety of absorbent applications.

Operations to extract the bentonite by PBL are unlikely to result in any source of conflict with B.C. Hydro for extraction of the coal.

Current investigation by PBL in September, 1992 consisted of sampling surface outcrops and drilling of a total of 8 shallow auger holes for a total of 232 ft (71 meters) of drilling. These auger holes were drilled in an attempt to delineate surface outcropping of claystone and to infill geological data. Also, plastic standpipe piezometers were placed in 6 of the holes to enable groundwater levels to be measured. Water in quantity would hamper bentonite mining because of the very sticky nature of the clay when wet. Also excess water adds to drying costs.

In addition, laboratory testing and market research studies were conducted. The testing, market research and field drilling supervision was performed by Nigel A. Skermer, P.Eng. consulting engineer, whose resume is appended.

2 Purpose of the Investigation, Testing and Studies

Bentonite clay is an industrial mineral having varied uses. The clay in the Hat Creek claims could find application for drilling muds, foundry mouldings, pelletising iron ore, as an absorbent and for use in the newly emerging environmental technology field, for example for liners and slurry trench walls. Most of these uses call for relatively low cost material. Thus the economics of developing the deposit are therefore important in determining whether the claims can be developed into a mine.

For the above reasons, the proximity to ground surface of the mineable clay is therefore important, i.e. the depth of overburden needs to be known. Also the presence of groundwater that could influence digging needs to be determined.

A considerable amount of information has been gathered from examination of surface outcrops of the clay on an axis pending southwest to northeast across the claims BEN 1 and BEN 2.

Investigations two years ago were designed to determine the feasibility of mining in the northwest and southeast corners of the claims where less was known on the proximity of the clay to the ground surface. The 1990 investigation consisted of shallow auger drilling in these areas.

The 1990 drilling was conclusive in determining that no bentonite claystone existed within the currently considered surface mineable depth of 10m in these two areas of the property.

The 1992 investigations therefore returned to other areas of the property where clay at shallow depth might be found. In particular the southwest corner of the claims was investigated, because little previous drilling had ever been performed in that area.

The 1992 field investigations were conducted in this area in order to answer, as in previous years, the following questions:

- does the bentonite clay subcrop within about 10m of the ground surface, so that excessive amounts of overburden would not need to be removed in order to mine the clay, and
- does groundwater occur at shallow depths in the overburden, which could lead to difficulties in digging the clay. For this purpose standpipe piezometers were installed in the auger drill holes.

As well as drilling investigations, laboratory testing of the clay and market research studies have been performed. These are described in greater detail in the following section of this report.

3 Details of the Work Performed and Findings.

Since 1990 the anticipated markets for the material have changed somewhat, with emphasis now being placed on the use of the bentonite for waste containment liners and covers, and for other environmental applications.

As a result the work in 1992 has been performed in three fields:

(a) Market research for use of the material in British Columbia;

(b) Further drilling investigations in the southwest corner of the claims where bentonite might be near enough to the surface to exploit economically. Also auger drilling techniques using varying bits and auger sizes were assessed critically; and

(c) Laboratory investigations carried out on hand samples taken in June 1992.

Because of outside commitments by other members of the Company, this year's investigations were conducted by Nigel A. Skermer, President of PBL.

Unlike metal mining, where the end uses of the product are well known, bentonite uses are changing rapidly. Also prices are highly variable depending on end usage. For this reason market research is a vital aspect of the determination of mine feasibility.

3.1 Marketing Efforts

Bentonite has more uses than any other mineral.* The price per ton, however, is extremely variable depending upon the end use and degree of refining, processing and mineral modification. At the lower price end market penetration is seriously hampered if transportation costs are high.

Because of the extensive drilling carried out in connection with the B.C. Hydro project, much is known about the extent, stratification and mineralogy of the clay on the PBL claims. The focus of efforts over the years has to be on marketing in order to bring the property into production. However as in previous years much of the effort by the principals of the Company (although not previously claimed as work performed) has been directed to this end. It involves considerable research and literature reviews. We now possess a very extensive library on bentonite clays. It could well be the most extensive on the subject in British Columbia, containing over 350 items of literature. This effort is now claimed as ~~a~~ valid current work needed to develop the property.

The market research by PBL over the past few years has shifted from long distance and overseas markets to a detailed examination of local markets in British Columbia. It is not now expected that PBL will gain its initial market penetration in the 4 large traditional bentonite markets: drilling muds, foundry moulding clays, pelletising of iron ore and kitty litter. Rather the emphasis is on new products for the expanding environmental industry, such as barriers to seepage, waste encapsulation etc. Tailor made clays are being developed in this field and this is where PBL's current interest lies. To illustrate this further two papers are enclosed in Appendix A, one from the American Society of Civil Engineers and the other a recent paper by the present writer, Nigel Skermer, in his capacity as a consulting engineer.

With the change of government in British Columbia and the emphasis on environmental protection, PBL has decided that the clay on their claims is likely to find application in local markets. Also this year's drilling and testing work has proven positive, and the Company aims to bring the property into production within the next 2 years.

3.2 Field Investigations

The site was visited in June 1992 to take small hand samples of about 10kg of clay from the Clay Cut. The location of the Clay Cut is shown on Figure 3 and a photo appears on Figure 4. It is a large open cut excavation dug by B.C. Hydro about 12 years ago. Although some slide material is mixed with glacial till, there are good exposures of the claystone in places. These samples, together with material sampled on earlier occasions, were used for the laboratory investigations described in subsection 3.3 below.

The current drilling investigations were conducted September 28-30, 1992. The rig was mobilized to Cache Creek on September 28th and drilling took place on September 29th and 30th.

Prior to drilling commencing, Mr. John Schalles, the local Range Permittee (453-9089) was contacted according to the terms of the permit. Mr. Schalles happened to be working in Hat Creek at the time.

The area under current investigation is the southwest corner of the claims. Access was gained via the Finney Creek forestry road, which commences just below the junction of the Hat Creek road with Highway 12. No other roads were traversed. Access to the drill area was made via the gate in the barbwire fence about 1/2 mile north of Finney Creek itself. Because the surface ground is active rangeland, the gate was immediately closed after each entry and re-entry of vehicles and equipment. Care was taken not to hinder the ranging operations in any way during the field investigations, all unsuccessful bore holes being backfilled for example. No litter was left on the property.

The drilling was carried out by Foundex Explorations of Surrey, British Columbia, using HT 1000 top drive rig, the same rig used on previous occasions. However, because of drilling difficulties experienced in the past, the actual method of auger drilling was examined critically. To this end the president of Foundex, Mr. Dennis Diggle, was present during the drilling on September 29th. Continuous hollow stem auger drilling was used because this is the normal method of investigating bentonite clays in the United States. It has the major advantage of providing continuous samples on the auger flight blades. It does nevertheless run into difficulties in penetrating gravelly fill cover, or conglomerate seams in the claystone unit. Very often refusal is met at shallow depths. It may be that future investigations will need a return to tricone and core drilling originally adopted during the early B.C. Hydro operations.

During the current operations various auger sizes and bit types were tried, in order to discover the optimum technique using this type of equipment. It was found that the best results were achieved with a 114mm (4½ins.) diameter auger and a bulldog drill bit.

A total of eight (8) auger holes were drilled to depths varying between 4m and 16.7m (13ft and 55ft) for a total depth 70.7m (232ft).

The locations of the boreholes are shown on Figures 3 and 5. *They are shown with respect to* DH802 performed by B.C. Hydro in 1976. However it is believed that the DH802 was incorrectly surveyed since its locations on the drawings by B.C. Hydro does not seem to fit existing topography as seen on the ground. In the next few weeks PBL will return to the property and resurvey the position DH802, since it is an important drill hole that penetrated nearly 190m of the lower claystone unit. If necessary a revised borehole location map will be resubmitted to the Mineral Titles Branch.

The borehole logs are shown in Appendix B. The results of the drilling are very encouraging. Although the till cover could not be penetrated in places, and although its thickness is probably quite variable, the clay is likely at relatively shallow depths in much of the southwest corner of the claims. At borehole 92-7 it was struck at very shallow depth, easily accessible by a simple open cut excavation. The quality of the clay also appeared good for PBL's intended purposes.

Various samples of the clay were taken and tests will be performed over the winter.

Drilling adjacent to DH802 i.e.in 92-3A and 92-3B again confirmed relatively shallow depths to clay. However there appears to be a persistent seepage zone at a depth of about 7m (23ft) that could hamper mining operations. It was noted early in the B.C. Hydro operations in 1976, and probably accounts for what is termed the "bentonite boils" immediately due north (about 50m) of this area.

Standpipe piezometers were installed in boreholes 92-1, 2, 3A, 4, 5 and 7. The tip elevations are as shown on the logs. To prevent damage by cattle to the upstanding portions of the piezometer pipe, as has happened to previous installations, the pipes are protected by 4ins. diameter black pvc pipe. The piezometers are 19mm (3/4ins) white pvc tubing with 450mm (18ins) slotted screen lengths. The tips are set in silica sand and the top portions sealed with bentonite pellets, the remainder of the hole being back-filled to surface.

3.3 Laboratory Investigations

Permeability tests were carried out in the private soil mechanics laboratory of Nigel Skermer. These consisted of constant head permeability tests carried out in a 90mm (3½ins) permeameter. The permeameter was designed to apply a maximum head of 250mm. The base of the permeameter consists of wire mesh screen with a Whatman's No. 1 filter paper cover. The clay sample lies on top of the filter and screen base. This is a fairly standard design.

The tests were conducted on tan coloured, oxidized bentonite clay, small samples of which were carefully obtained by hand sampling at select locations from the walls of the Clay Cut. The clay was taken from slickensided seams, the slicks often containing manganese coatings. The clay here also contains occasional calcite crystals. The clay is therefore expected to be predominately a calcium bentonite in accordance with earlier mineralogical testing.

The clay specimen used in the permeameter was 25mm thick and the initial series of tests were carried out on essentially uncompacted sedimented material. Later tests are to be conducted over the winter on compacted clay.

The object of the tests was to determine permeability under different permeating fluids, namely fresh water, salt water and animal manure fluid. The purpose of using the last mentioned permeant is with regard to use of the bentonite for certain environmental protection purposes in the agricultural field.

Because of the very low permeability of the clay the tests are lengthy and take weeks to perform.

The test results are very promising. Even without compaction, the sedimented Hat Creek clay yields, a permeability as low as 8×10^{-8}cm/sec with tap water. This is under a severe hydraulic gradient of 10:1. This means that the clay can be used for lining freshwater ponds.

Even more encouraging is the permeability under salt water (sea water) where values less than 4×10^{-9}cm/sec were found. This is probably because the large sodium molecule cannot penetrate the clay matrix when small calcium molecules form the dominant cation as is the case with the Hat Creek clay.

Tests using urine and other animal manure leachate are still on-going, but preliminary findings are that the weak uric acid does not destroy the clay. The clay changes colour from tan to blue-grey, probably as a reduction by glucose of the small iron content from ferric back to the ferrous state. The ferrous state is how the clay is normally seen on first exposure of drill samples taken from depths greater than about 6m, below the zone of oxidation.

Tests were also conducted on the same clay samples to see if cation exchange could be brought about., Most European bentonites, particularly English and Bavarian clays, are calcium montmorillonites. The Europeans product sodium bentonite for drilling and civil engineering uses by cation exchange using sodium carbonate.

Tests were therefore performed on the Hat Creek clay. Sodium carbonate was used, obtained from sources nearby at 100 Mile House, in this case Anita Lake, the sample being taken by the writer as "winter crystal" in November 1990. A small percentage of sodium carbonate was mixed with the wet clay and allowed to react. The material was then tested for swelling and gel formation. Although the swelling is somewhat improved the gel formation is not as good as Wyoming bentonite. Further experiments will be conducted to investigate different mixing techniques and to find the optimum proportion of sodium carbonate.

4 Costs Claimed

The following costs were claimed in this report of assessment credit:

(a) Drilling costs invoiced by Foundex Explorations Ltd.,

(b) Engineering costs invoiced by Nigel A. Skermer, P.Eng., for the layout of the drilling program, field direction and supervision and logging of the drilling;

(c) Laboratory testing, market research and report writing by Nigel A. Skermer, P.Eng.,

Total costs for this assessment work is $ 21,979.87. Detailed invoices are shown in Appendix C.

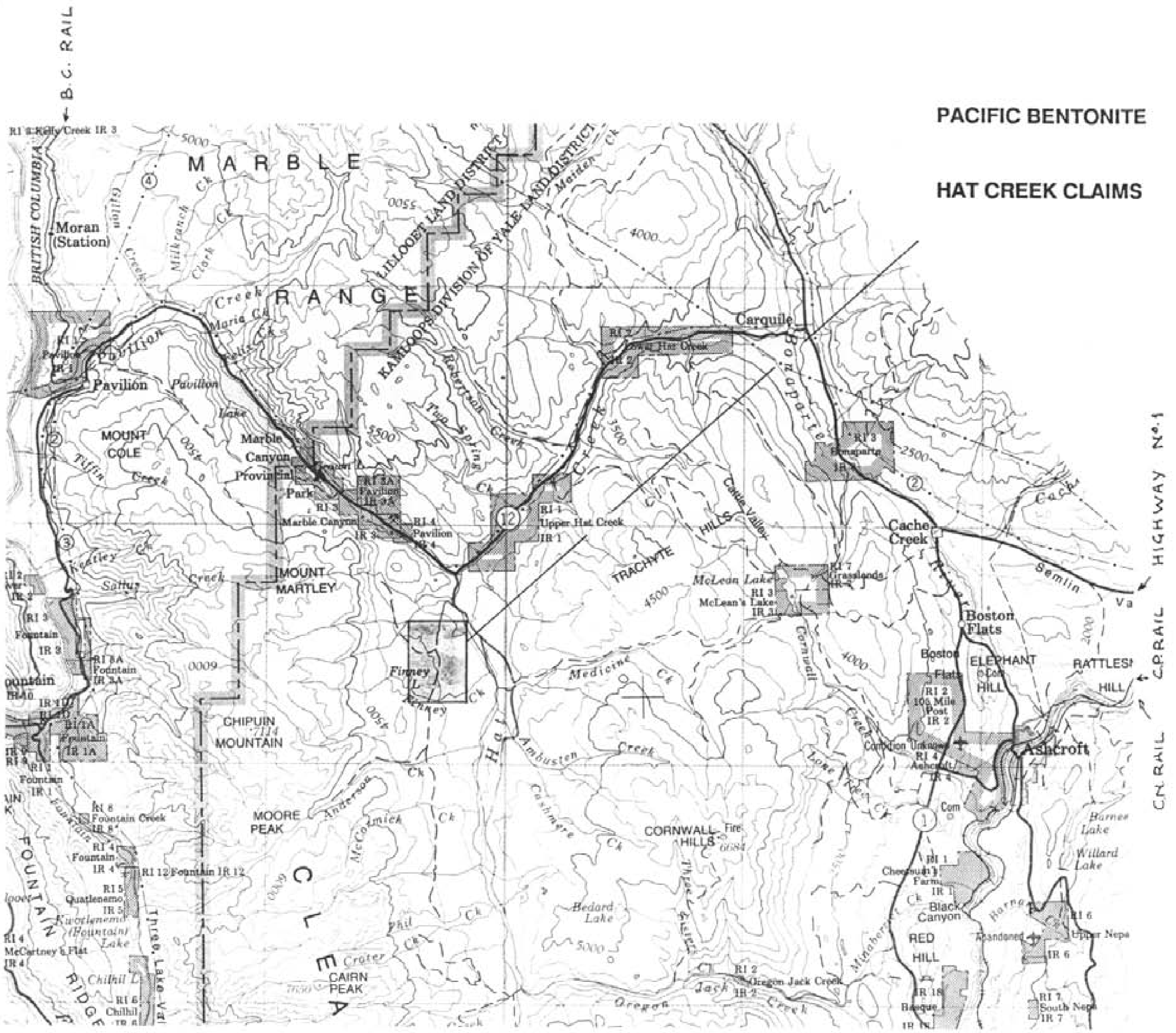
PROFESSIONAL ENGINEER
PROVINCE OF BRITISH COLUMBIA
N. A. SKERMER

• Quote from paper by I. Odum, American Colloid Company, at the 1989 Society of Mining Engineers meeting in Chicago.

LOCATION OF PROPERTY

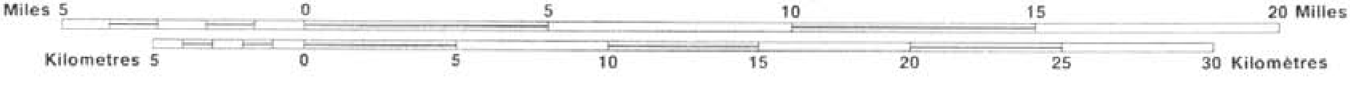
PACIFIC BENTONITE

HAT CREEK CLAIMS

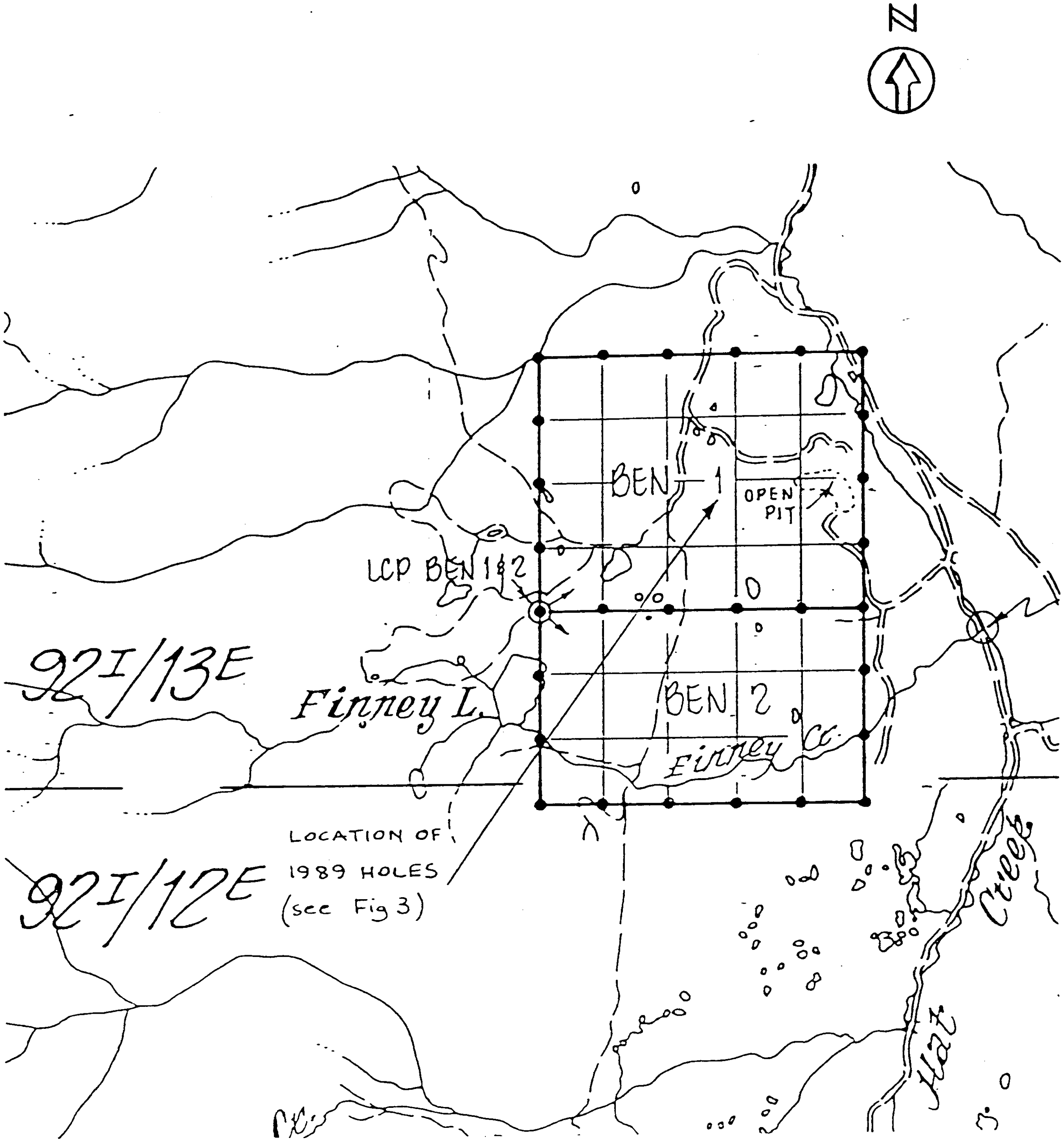


Roads:	Routes:		
hard surface	revêtement dur	dual highway double chaussée	more than 2 lanes plus de 2 voies
hard surface	revêtement dur	2 lanes 2 voies	less than 2 lanes moins de 2 voies
loose or stabilized surface, all weather	gravier, aggloméré, toute saison	2 lanes or more 2 voies ou plus	less than 2 lanes moins de 2 voies
loose surface, dry weather	de gravier, temps sec		
cart track	de terre		

Scale 1:250 000 Échelle



PACIFIC BENTONITE LTD *Fig. 1.*



Pacific Bentonite Ltd: "Ben 1 and Ben 2" mineral claims (35 units, 875 ha)

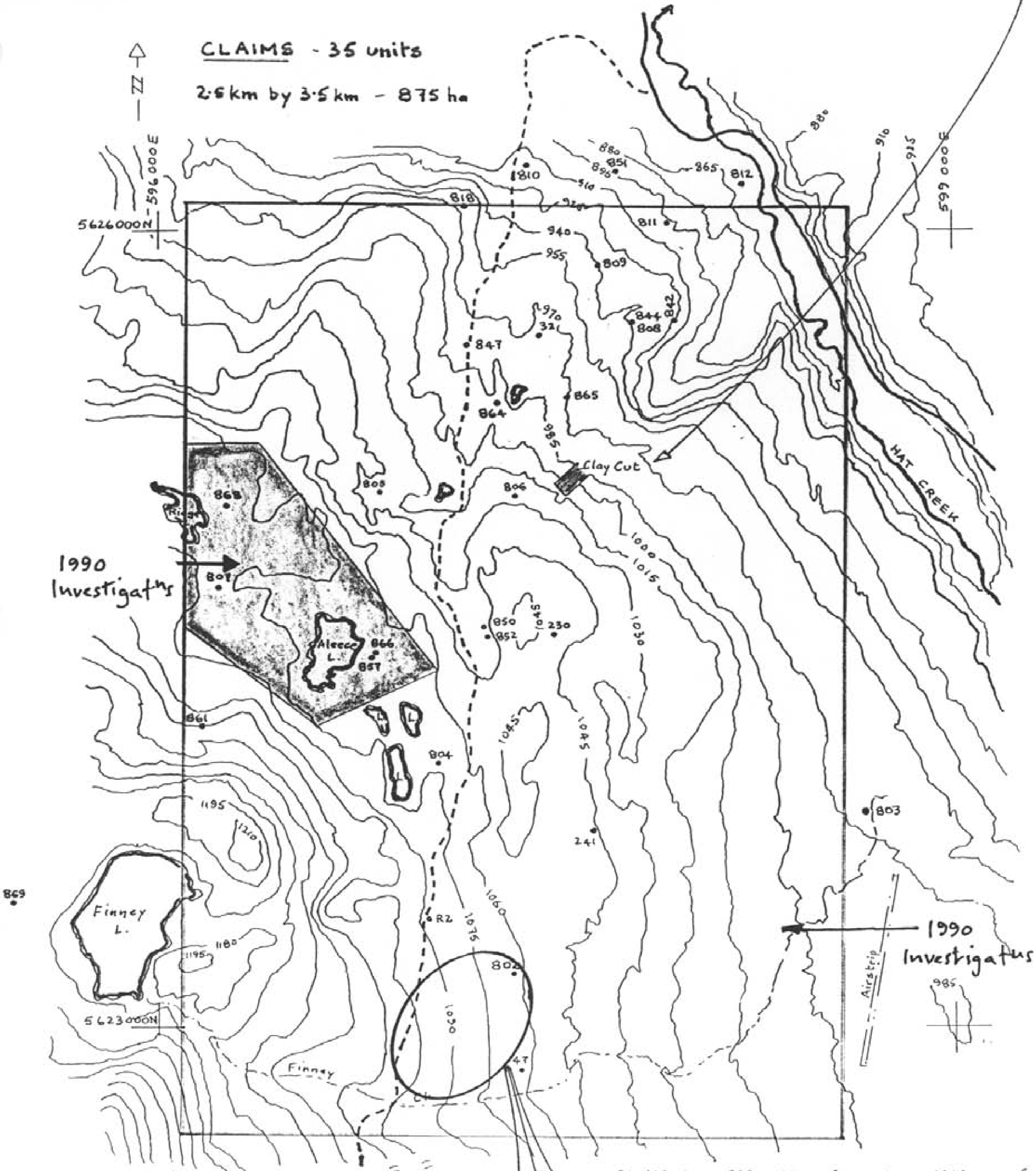
Scale 1: 50,000

LOCATION OF CLAIMS

PACIFIC BENTONITE

Fig. 2

Location of Clay Cut, see Fig. 4.



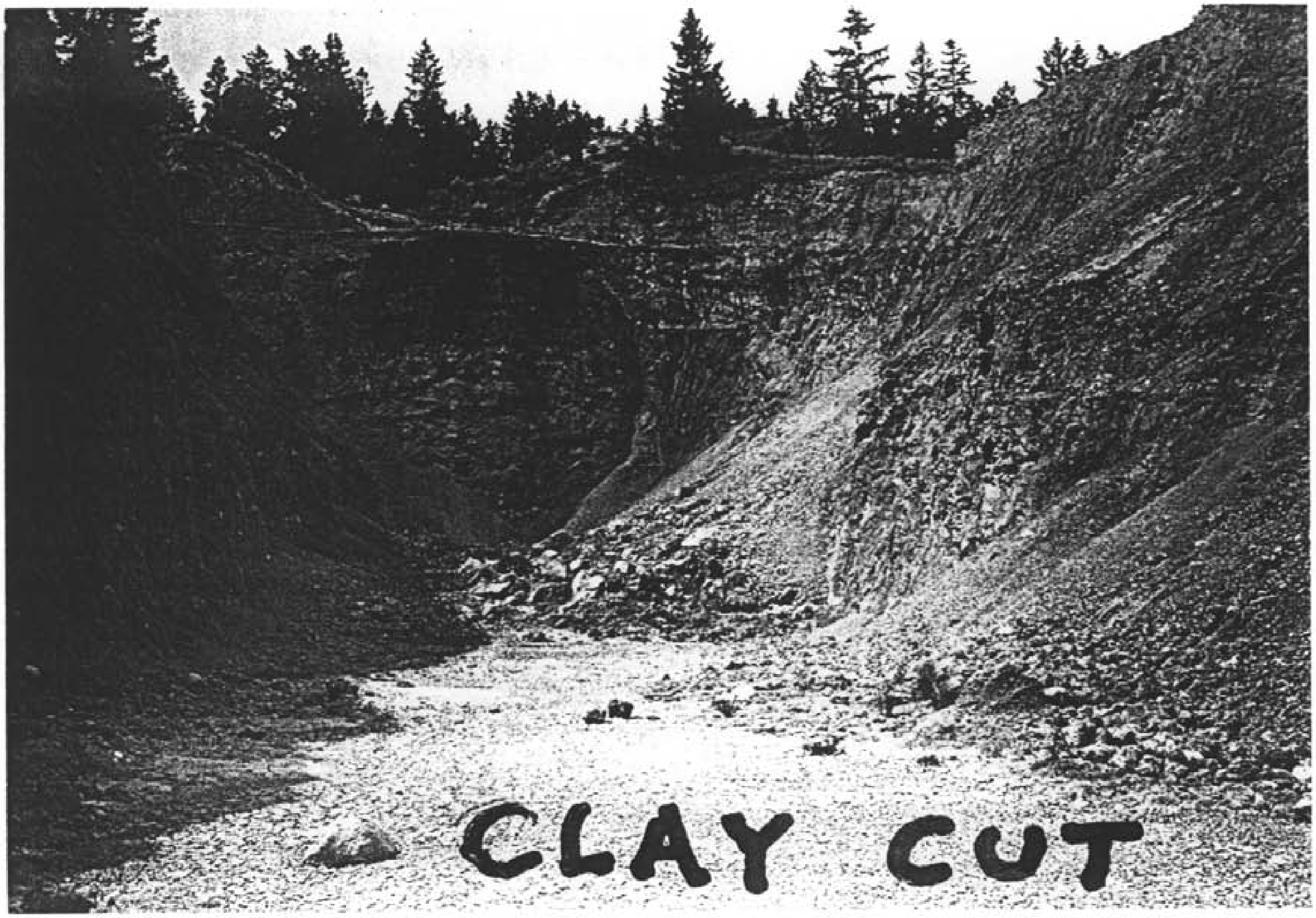
1992 Field Investigations

see Fig. 5.

N.A. Skermer, P.Eng
1 October 1992

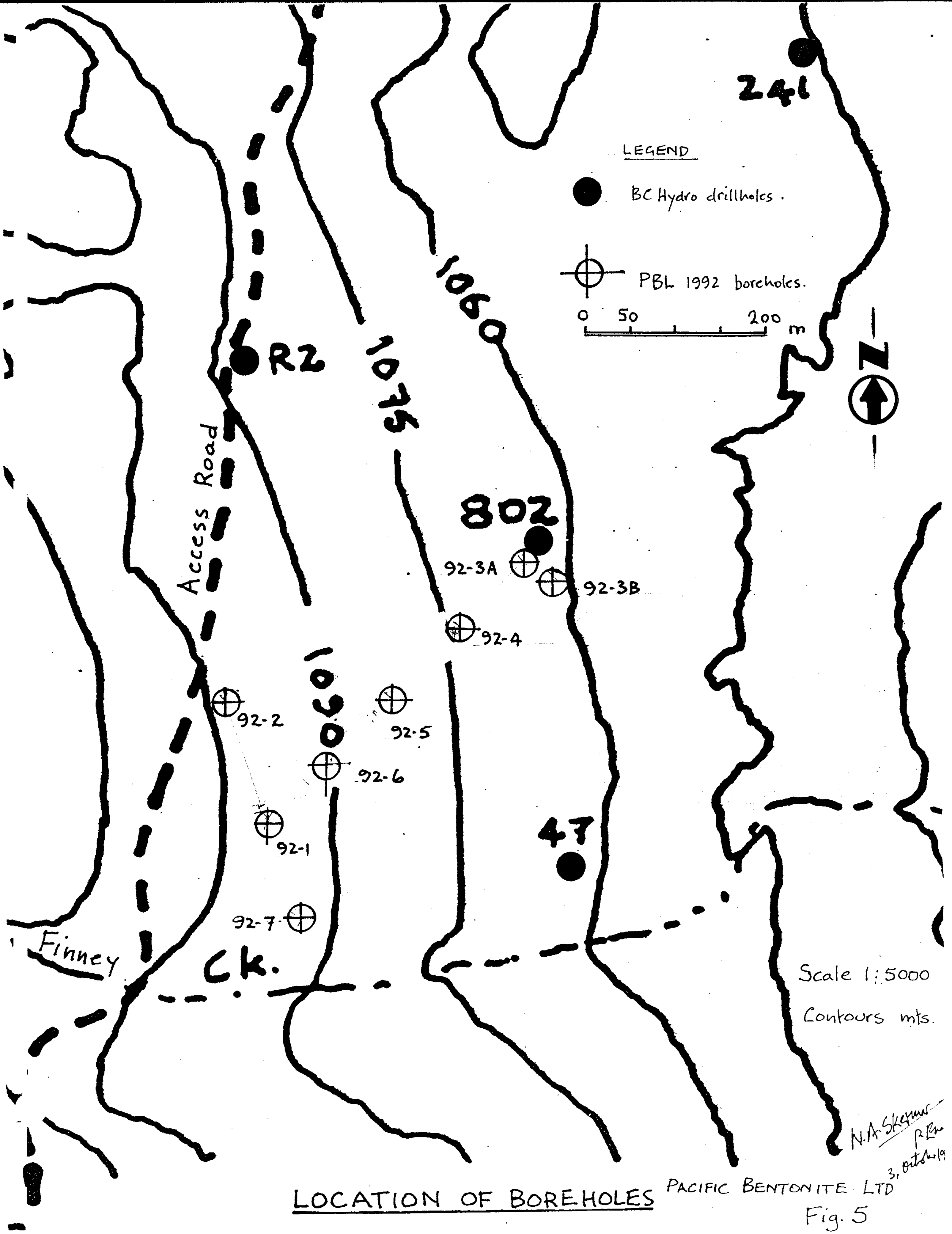
PACIFIC BENTONITE LTD

Fig. 3.



PACIFIC BENTONITE LTD

Fig 4.



N.A. Skermer P.Eng 3, October 19

LOCATION OF BOREHOLES

PACIFIC BENTONITE LTD

Fig. 5

APPENDIX A

Uses of Bentonite in Field on Waste Containment

NO FEET OF CLAY

Organically modified clays are carving out a niche in a variety of waste treatment applications.

GEORGE R. ALTHER
JEFFREY C. EVANS
STEPHEN E. PANCOSKI

As Superfund site remediation chugs along, the methods of dealing with hazardous waste have similarly evolved. At one time, old-fashioned "excavation and removal" was the popular choice for treating pollutants, but stabilization and solidification has since emerged as a viable option. And innovative technology—specifically modified clays—has helped pave the way.

The key to waste stabilization is to produce a material that minimizes the leaching rate of hazardous pollutants. Conventional agents, such as cement, cement kiln dust or fly ash, are successful in stabilizing metal-bearing wastes, but they are generally less effective when used exclusively with organic wastes. The organic constituents tend to retard the cementitious reactions, inhibiting the formation of a solid monolithic mass.

Also, the organic components may be easily leached from the solidified mass. To overcome these difficulties, large amounts of cementitious stabilizing agents are added, which can greatly increase both the volume of the waste and the cost of the process.

The arrival of the relatively new, organically modified clays, however, can help solve the problem. When these clays are mixed with conventional stabilization agents, they adsorb and retain pollutants while solidifying organic wastes into a stable mass with low leaching potential.

Waste stabilization is not the only environmental application for organically modified clays: They're also on the market for water treatment, and they have shown potential for spill control and as tank and landfill liners. Their future use in landfills is especially crucial because of EPA's concern that both geomembrane and natural clay liners may be subject to degradation in the presence of organic contaminants. Furthermore, organic contaminants may migrate through conventional materials in response to chemical diffusion gradients.

CLAY TESTING

To produce a modified clay, an unmodified clay mineral reacts with an organic compound, producing an ion exchange. To manufacture the clays, either a wet or a dry method is used. In the wet process, an unmodified clay is mixed with water, forming a slurry, which is centrifuged to remove inert, nonclay minerals. The supernatant, which contains ultrapure clay, then reacts with the specified organic compound. The mixture is filtered, dried and ground.

In the dry process, limited amounts of water are added to an unmodified clay. The clay then reacts with the organic compound in a mixer, pug mill or extrusion device. Finally, the reacted material is dried and ground, but since centrifugation is not performed, some impurities may still exist in the finished clay product.

A sedimentation or "free-swell" test may be conducted to evaluate the relative adsorption capacity of a number of commercially available organically modified clays. In past tests, 50 ml of test fluid was placed in a 100 ml graduated cylinder, and 2.5 g of clay was sprinkled into the fluid and allowed to settle to the bottom of the cylinder. The mixture was periodically swirled as necessary to assure sufficient contact between the clay and the test liquid.

The volume of the clay in the graduated cylinder (the free-swell volume) was recorded immediately after the clay settled and again 24 hours later to see if any changes had occurred. In general, little or no change was observed between the initial and 24 hour free-swell volumes. This value is equilibrium or free-swell volume.

By analyzing the average free-swell volume, experts can compare a number of modified clays with a range of organic fluids. Clays used in the free-swell tests included attalpulgite and bentonite, the brand names bondtone, claytone APA, claytone 40, 2HT, P-1, P-11, P-40, PC-1, PT-1, suspentone and TS-55. Test fluids used were acetic acid, acetone, aniline, carbon tetrachloride, deionized water, diesel fuel, hexane, kerosene, unleaded gasoline and xylene.

The analysis revealed that the organically modified clays tested have an average free-swell volume between 11 and 35 ml.

The wet-process clays with the highest average free-swell volumes are Baragel 3000 (34.3 ml), Benathix 1-4-1 (32.1 ml) and Tixogel SP (31.6 ml). The dry-process clays with the highest free-swell volumes are PC-1 (23.8 ml) and TS-55 (23.1 ml).

Meanwhile, bentonite and attalpulgite, the two unmodified clays, have the lowest average free-swell volumes, indicating they did not swell appreciably in the presence of the concentrated organic fluids. Clays such as bentonite have been used for many years as pond and landfill liners because of their low permeability to water, but the low permeability has been adversely affected by organic-containing fluids.

Of course, the swell volume is only an indicator of the clay's adsorption capacity and may not adequately quantify its performance during some hazardous-waste applications. Also, a clay's cost must be compared to its performance before it's selected for a particular application.

The more accurate evaluation method is the time-consuming method of constructing adsorption isotherms. However, just because a clay swells only slightly or not at all in a hydrocarbon fluid does not necessarily mean that it has no adsorption capacity.

PUTTING CLAY TO WORK

Some of the applications of organically modified clays are developed and in the marketplace; others have recently been proposed.

- Waste stabilization. The key to this process is using the clays in conjunction with conventional cement-based or pozzolanic additives to reduce the mobility of organic constituents from the stabilized matrix. The clay, with organic contaminants bound within its structure, is macroencapsulated in a cementitious matrix. Mobility has in fact been reduced, and the technology is the subject of several patents. The technique has become increasingly widespread at Superfund site remediations.
- Water treatment. In this process, the aqueous solution is filtered through modified clay and the organic contaminants are adsorbed. Unlike activated carbon, which adsorbs organic contaminants through surface-related phenomena, organically modified clays swell as the contaminants are sorbed into the clay structure. Thus, the organic molecules of the contaminants preferably partition into the organic phase of the organoclay instead of the aqueous phase. Volatile organics are poorly adsorbed, but oils and greases are readily adsorbed.

Organically modified clays are typically combined with other water treatment technologies. When used in a treatment system upstream from activated carbon, for example, the carbon life is greatly extended as a result of the removal of high-molecular-weight organics. Several commercially available products (Bentec's Ecosorb, Calgon's Klensorb 100TM and Electrum's Organosorb) contain an organically modified clay to remove organics from a waste stream. The organophilic clay in these products is used with an anthracite filter media to provide an effective column filtration medium in water and wastewater treatment.

The combination of this mixed media and granular-activated-carbon adsorption facilitates the removal of a broad range of both soluble and insoluble compounds. The influent and effluent oil concentrations, for an oily steam condensate filtered with a granular organoclay and anthracite filter media, resulted in a projected annual savings of $150,000 for a 500–600 gpm system. In another application, the organically modified clay removes nonvolatiles prior to air stripping, thereby increasing the efficiency of the system.

- Spill control. As demonstrated in laboratory studies, organically modified clays will either float on the surface or sink to the bottom of an aqueous solution, depending on the nature of the organic modification. For example, a diesel-fuel spill, such as the one on the Monongahela River in Pittsburgh (where an organoclay was tested), can be held within the clay crystalline structure for cleanup and disposal. For a spill where the materials sink, the clays could likewise be selected to sink through the water and sorb the spilled fluid.
- Tank liners. Fuel-oil storage tanks are typically surrounded with a liner and berm system to contain the fuel oil should a leak occur. As a result of the impervious nature of the liners used in these systems, they also contain precipitation. As an alternative to conventional liner systems, organically modified clays can conceivably be used. A clay liner would permit precipitation to flow down through the liner without accumulating in the containment system.

In the event of a tank puncture and leak, the organically modified clay will swell in the presence of the fuel and form an impervious barrier layer. This would prevent migration of contaminants into the subsurface. It may also be possible to use the clays as secondary containment barriers beneath or around storage tanks in a similar manner.

- Landfill liners. The technology for landfill liners has been evolving in recent years toward multimedia barrier layers, which could optimize environmental protection. Presently, liner systems include both geomembrane barrier layers and natural clay barriers, but these materials may react adversely to organic contaminants.

A landfill-liner system, though, could potentially include a barrier layer composed of an organically modified clay. In this way, the multimedia liner system would perform better in the presence of organic contaminants. The sorptive capacity of these materials would significantly reduce the rate of organic contaminant transport across the liner system. Like modified-clay tank liners, the clay landfill-liner technology is on the drawing board, but has not yet been implemented.

SOME APPLICATIONS OF MODIFIED CLAYS ARE ON THE MARKET. OTHERS ARE ON THE DRAWING BOARD.

In one liner system, Gunseal, a granular bentonite manufactured by the Paramount Co., Spearfish, S.D., is glued to a synthetic liner. The system can provide the best of both worlds: If the synthetic liner is punctured, the bentonite swells upon contact with the water, and the system is, in effect, self-healing. Paramount and Bentec are combining their respective technologies by glueing an organically modified clay to the synthetic liner.

CREDITS

Many of these investigations were part of a research project funded by the Ben Franklin Partnership of Pennsylvania; the Sun Refining and Marketing Co., Marcus Hook, Pa.; and The Earth Technology Corp., Long Beach, Calif. Manufacturers supplying clays for the free-swell tests mentioned earlier were: Bentec, Inc., Ferndale, Mich.; Engelhard Specialty Chemicals, Edison, N.J.; NL Baroid, Houston; Silicate Technology Corp., Scottsdale, Ariz.; United Catalyst, Louisville, Ky.; and NL Chemicals, Hightstown, N.J.

George R. Alther is president of Bentec, Inc., Ferndale, Mich., a manufacturer of organoclays. Jeffrey C. Evans is an associate professor of civil engineering at Bucknell University, Lewisburg, Pa. Stephen E. Pancoski is an engineer with Gannett-Fleming Geotechnical, Inc., Harrisburg, Pa.

Environmental Issues and Waste Management in Energy and Minerals Production, Singhal et al. (eds)
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Natural and artificial barriers to seepage

Nigel A.Skermer
Steffen Robertson and Kirsten Inc., Canada

Rhino G.Röhrs
Robertson Barrier Systems Corporation

ABSTRACT

Much has been written on liners. This paper pulls together in a concise manner the pros and cons of artificial and natural liners. The term artificial can apply to both plastic and clay liners. Natural liners can only be clay and other soil liners in their undisturbed condition in the site's subgrade. This is a new way of looking at these barriers to seepage. The term geosynthetic can be misunderstood and therefore misleading. Most people would restrict its use to plastics, but in fact many clays, and other highly absorbent substances such as zeolites, are clearly geosynthesized materials. This is not simply an academic distinction.

An obvious consideration therefore is the control that can be exercised over a manufactured material, be it plastic or clay, and the degree of security that this can bring to a waste contaminant system. Along with this goes the uncertainties associated with natural subgrade strata. The division then between artificial and natural barriers seems far less academic.

Geotechnical engineers, especially those experienced in clays, know the enormous care and attention that needs to be given to natural formations before success can be assured. Seemingly homogenous, isotropic subgrades do not exist. Intricate pattern of deposition such as lens, bedding and varves and subsequent structural features such as fissures and root holes, offer ample causes for concern where seepage is to be prevented. On the other hand the adsorption capabilities of a deep natural subgrade can be well utilized.

Difficulties in manufacturing artificial liners can apply to both plastic and clay materials. Many of the difficulties with clays can be overcome by referring back to the sound practices that have been established for the construction of clay cores in earth dams. Some of this experience is centuries old having been evolved for the watertight linings of the early canals.

Uncertainties with plastic liners usually centre around the jointing issue. Methods of joint construction are reviewed. The advantages of a patented, testable, double plastic liner are explained.

1 INTRODUCTION

We present no new data. Rather we attempt to stand back and look at the overall picture of barriers to seepage, both natural and synthetic.

Most people mean plastic when thinking of geosynthetics, and clay or other common earth materials when thinking of natural barriers. However, although clay may be natural in its in-situ state in the ground, it is really a constructed material by the time it is placed in a compacted liner or in a slurry trench wall. Furthermore the clay may be refined, processed and mixed with carefully determined proportions of fine sand before application. Special clays, such as organoclays, are what one might call "designer clays", and these too are finding application in waste containment facilities. Is it not true to say, therefore, that such materials are geosynthesized? If so, we might wish to think in terms of two classes of barriers to seepage:

- Natural Geologic Barriers, where the geological host materials have characteristics sufficiently impenetrable to act as suitable containment sites without treatment;
- Artificial Barriers, where use is made of materials that are processed or manufactured and constructed under carefully controlled field conditions to achieve as near as possible a uniform product.

The first classification at first sight looks like the "do nothing" approach. In fact, much effort may be expended in characterizing the permeability of the host site, and analyzed whether or not it is sufficiently leakproof to do the job. It may be that on a large scheme, apart from minor treatment at certain places, the greater part of the site is acceptable as it stands. In fact, such is the case for the vast majority of the wastes that we generate. It applies to most mining wastes. Apart from a tailings dam across a narrow section of the valley, the majority of impoundment basins act in their natural state, as perfectly acceptable barriers to seepage. As well as low permeability, host rocks and soils, a natural hydraulic barrier often exists, particularly in steep mountain valleys, by virtue of hydraulic gradients acting in an inwards direction. This approach was proposed by Matich and Tao (1984, and 1987) for disposal of tailings in worked out open pit mines. The hydraulic barrier is important since normally the placement of either plastic or clay liners on steep pit walls is impractical.

Finally, natural seepage barriers have going for them the fact that the materials have withstood the test of time, at least post-glacial time. Therefore, unless particularly aggressive new chemical and physical changes are brought about by introducing the waste, there is little reason why natural barriers should not continue to function for many, many years indeed.

Such level of comfort cannot be said for artificial barriers. Clay liners properly compacted ought to function satisfactorily, and it seems as though geoplastic material ought to be capable of being designed for a long service life. But the record of proven performance is not long, particularly with geoplastics, possibly not more than about 25 years. With clays at least a somewhat longer record exists, in the use of such materials as the impermeable cores for earth dams: in that instance the record stretches well back into the 19th century, and occasionally into the 18th century. With both types of synthesized materials, however, the record is one of physical and biological stability. Only in recent years has chemical stability become a concern with the requirement to contain municipal, industrial and hazardous wastes. In truth, the stability of geoplastics in harsh chemical environments is in the realm of prediction, some of it good based on carefully controlled laboratory tests, but still prediction. At the ASTM Symposium on Microstructure and the Performance of Geosynthetics held in Orlando, Florida in 1989, the Chairman, Ian Peggs, made the following important statement:

> "An incredible amount of confidence has been placed in the capability of geosynthetics to perform adequately over long periods of time in very critical applications, such as for liners containing hazardous wastes. If supporting technical data are not generated to confirm this confidence, and if data are not generated to guard against the inevitable deficiencies of geosynthetics, then this confidence will be severely questioned. We must be ready for the surprises that will occur." [Note the use of the word "will" not "may" occur.]

The quoting of his comments is in no way meant to decry the use of geosynthetics, but merely to caution against overconfidence in their performance.

Engineers involved with the design of earth dams, and particularly those engaged in dam rehabilitation work, know only too well the problems that can arise with clay cores, and not merely with dams a hundred years but also sometimes with new structures. Why, therefore, should geosynthetics be the panacea? Of course, they are not. They have their place alongside, and sometimes in association with, soil liners and cutoff walls.

Clearly, therefore, artificial barriers have their limitations, but in their favour lies the comfort that comes from knowing that the materials can be manufactured, and the barriers constructed, with the exercise of any amount of care and control, depending on the requirements and the money available. No naturally occurring barrier can ever be investigated to the extent necessary to yield parameters to which can be attached as high a degree of statistical confidence as for the properties of a known constructed barrier. In fact, in many respects, geotechnical field investigations are at a crude and lowly level of development. Jean-Yves Perez, in his keynote address at the 1991 American Society of Civil Engineers, Geotechnical Division conference, had the following astute comments to make:

> "The measurement of average properties will not satisfy our future subsurface information needs. The performance of structures (especially liner structures and those designed to contain contaminants or large volumes of water) is affected by discrete zones of weakness and high permeability or by pockets of highly concentrated chemicals. We need tools that allow us to detect and measure specific, small attributes of the substructure with reliability and efficiency....We have the means to analyze the composition and density of stars and planets millions of light years away. We should be able to measure detailed soil properties a few meters under our own feet."

We should, indeed, but for many years to come the information is likely to remain more or less fragmentary, and thus may limit confidence in site suitability.

2 NATURAL GEOLOGIC BARRIERS

Siting of a containment or impoundment facility is a primary decision. It may be that there is little choice. However, usually a variety of choices or a large geographical area is available for consideration. The choice of site may be critical to determine whether a site can be used in its natural condition, or whether artificial barriers need to be incorporated. Choice of site involves a screening process, and where seepage is concerned key factors are topography, geology, hydrology and groundwater. The process of site selection is described in a number of publications. See, for example, Vick (1990) concerning tailings dams, or Collins and Sankin (1981) in the chapter on hazardous waste siting.

A natural geologic barrier is like a prison without walls. The surrounding environment must be sufficiently enclosing that nothing can escape. The man imprisoned on an island in shark-infested waters, or sent to some arctic camp surrounded by miles of frozen tundra, usually stays put. The difficulty with a natural geologic barrier is in determining whether the surrounding environment is sufficiently inhibiting to prevent escape of fluids. In the end the determination boils down to judgment. It is the same judgment call that applies in geotechnical engineering to determine foundation conditions for a dam, which is just another barrier to seepage. We can find no better depiction of the difficulties in determining subsoil conditions than that given by Terzaghi and Peck (1967). It may be a quarter of a century old, but it is well worth revisiting:

> "Causes of Misjudgment of Subsoil Conditions
>
> No matter what may be the subsoil conditions and the program for borings and soundings, the exploration furnishes information only concerning the sequence of materials along vertical lines, commonly spaced no closer than 50 ft, and concerning the significant physical properties of what are believed to be representative samples. On the basis of this rather fragmentary information, the designer is compelled to construct a soil profile by interpolation between drill holes and samples, to divide the subsoil into zones consisting of materials with approximately the same engineering properties, and to estimate for each zone the average values of the soil parameters that appear in his equations. Thereafter he forgets the real soils and operates with

fictitious materials. Hence, the degree of reliability of the results of his computations depends entirely on the differences between the real and the ideal subsoil. If an unfavourable difference of an essential nature has escaped his attention, the design he has prepared on the basis of his data may turn out to be unsatisfactory in spite of conscientious subsoil exploration.

Experience has shown that the causes of fatal misjudgment of the subsoil conditions may be divided into three categories:

1. Influence on the test results of excessive sample disturbance or of significant differences between test and field conditions.

2. Failure to recognize or judge correctly the most unfavourable subsoil conditions compatible with the field data.

3. Inadequate contact between the design and construction organizations, resulting in failure to detect significant departures of conditions or of construction procedures from those the designer anticipated or specified."

In part, Terzaghi had in mind water storage dams where a certain amount of seepage loss can be accepted, provided that the economics of the scheme are not affected and provided that seepage pressures do not endanger the dam. For the storage of waste we seek in some instances to exclude virtually all fluid loss. How much more demanding therefore becomes the need for adequate subsurface exploration?

The difficulties are not insurmountable, however, and improvements have been made over the years. Rowe (1971), for example, discusses representative soil sampling and the influence of fabric on the permeability of glacial till, organic clay and fissured clay. He argues for the need to record fabric and the need for sufficiently large diameter samples in order to make such determinations.

Granted that the permeability of the site be determined, the soils may also have very useful properties of adsorption. Heavy metals, for example, can be attenuated by seepage through natural materials, both soil and rock. Interaction takes place between the fluid and solid phase as a result of chemical or physiochemical disequilibrium. Often the result is that metals in the fluid are removed onto the solid resulting in a cleaning action on the seeping fluid. This is more properly termed hydrogeochemical attenuation. It can apply also to artificial clay barriers. An important place of research in this field is the University of Western Ontario, Geotechnical Research Centre. They have carried out very detailed studies over a long time span at the domestic landfill site at Sarnia, Ontario, founded on glacial till. A useful summary paper of their work is Rowe (1988).

3 ARTIFICIAL BARRIERS

Within this category we are including two subcategories. First, the various forms of constructed clay barriers including liners, covers and slurry walls. Other cementitious and adsorptive materials such as cement, fly ash and zeolites can be included. Secondly, we include the flexible membrane liners (FML) constructed from plastics, the so-called geosynthetics.

3.1 Clay Barriers

3.1.1 Clay as a Material

Because of their low permeability and resistance to mineralogical changes, clays can be useful for surrounding barriers to contain waste. Clays are natural argillaceous materials, the three most common types being kaolinite, illite and smectite. The latter is commonly called bentonite, a naturally occurring clay, the major constituent of which is the clay mineral montmorillonite, a member of the smectite group of clay minerals. Bentonites are of two main types. The first is high swelling bentonite where the principal clay mineral is monovalent sodium montmorillonite. The second is low swelling bentonite, the clay mineral being divalent calcium montmorillonite. Both types have their uses. It is important to understand, however, that the sodium and calcium ions are the exchangeable cations, and their stability needs to be examined in the presence of the fluids released from the waste. A simple example is the action of common salt on sodium bentonite, which causes the clay to floculate and the permeability of the mass to increase. In salt water applications, therefore, the clay mineral attapulgite is often used. Similarly, under prolonged exposure, calcium cations will displace sodium, the tendency being for the higher valency cations to replace those of lower valency. High swelling is associated with the monovalent ions sodium and lithium, the latter being the much rarer variety called hectorite from California. Clay mineralogy is a subject in itself, and the reader is referred to Grim (1958), Van Olphen (1977) or other similar texts. Much is known about bentonites, however, because of the extensive use in oil well drilling fluids and many other industrial applications.

Although kaolinites and illites can be used in clay barriers, much of the research centers around bentonites. Besides low permeability, the high cation exchange capacity (CEC) and adsorption properties of bentonites render them particularly useful provided their particular application is chosen with care. The adsorptive properties have been known for thousands of years, Fullers Earth, basically calcium bentonite, having been the ancient substance used for the degreasing and cleaning of woollen cloth, see Robertson (1986). The adsorbent and bleaching properties of bentonites were studied extensively in the 1930's and 1940's by the United States Geological Survey, see Nutting (1943). Some of these clays are special acid activated, calcium montmorillonites, in which the mineral is stripped to a mere skeletal structure for use as an absorbent medium. A number of bentonites are specially processed to yield the required chemical composition, for example, American Colloid Company, Super Saline bentonite. Special organoclays are currently being designed with certain waste containment applications in mind. The organically modified bentonites, also called organophilic bentonites, which swell and disperse in organic fluids are natural sodium bentonites exchanged with quarternary ammonium cations. They were first described by Jordan (1949), but modern usage for waste treatment of these "designer clays" is described by Cadena (1989) and Alther, et al (1990).

While clay is indeed useful as a barrier material we caution against inappropriate usage. As Hoddinott and Lambe (1990) have pointed out, the chemical makeup of the fluid seeping through clay can have a marked influence on the physical behaviour. The vivid analogy of a rusty machine can be used. The steel in a car, for example, gradually corrodes until one day all that is needed is a small bump and the "old rusty heap" collapses. The same can happen to the bonds between clay particles in a too harsh chemical environment. Papers in the volume by Hoddinott and Lambe above discuss researches carried out into the physio-chemical behaviour of bentonites and natural clays. Other applications, research and analysis for the use of clay in waste containment barriers appear in the proceedings of the symposium held in the Royal Technical Institute in Stockholm, see Pusch (1985). Topics covered also included clay barriers for the isolation of high level radioactive waste. Similar research on the use of bentonites is being carried out by Atomic Energy of Canada.

Erosion and dispersion of clay leading to piping failures is a factor that needs to be considered when using clay in liners. Dispersion of clay particles and subsequent piping has been a factor responsible for the failure of a number of earth dams. Filters containing some fine sand sizes will generally control piping of dispersive clays. Calcium montmorillonite has a higher erosion rate than sodium montmorillonite. Dispersive clays and piping problems are discussed in Sherard and Decker (1977) and Lovell and Wiltshire (1987).

3.1.2 Compacted Clay Membranes

Compacted Clay Liners (CCL) and covers can vary in thickness from less than 300 mm to greater than 1 m. The technology for compacting clay properly is well understood, although not always put into practice. We will not repeat things here other than to highlight one or two issues of special importance worthy of repetition in our opinion. Good up-to-date summaries can be found in Mitchell and Jaber (1990), and Daniel (1990).

The main reason for choosing a CCL is to achieve low permeability, and the secret lies in proper compaction. The clay should be compacted a few percent wet of optimum moisture content. Kneading compaction should be performed using at least five passes of a heavy, at least 20 t, sheepsfoot roller in thin lifts less than the height of the compactor's feet, so that bonding and keying between lifts is achieved. This has been known since Proctor's early work on embankment dam construction 60 years ago. However, it seems on some recentprojects to have been overlooked. Low permeability cannot be achieved if the clay is too dry at the time of compaction. This was demonstrated on laboratory compacted samples in a classic paper by Mitchell, et al (1965). Figure 1 is taken from their paper and shows the dramatic decrease in permeability with increase in molding water content of the clay. Permeability decreases of two to three orders of magnitude are common with increasing water content coupled with increasing compactive effort. Water content of course should not be too high otherwise the clay sticks to the roller and cannot be compacted. Clay clod sizes should be minimized, material being pulverized prior to wetting, and thorough moisture conditioning allowed so that the clay can reach equilibrium prior to compaction. Clay compacted on sloping faces should not be used on slopes steeper than 3 horizontal to 1 vertical. Test fills prior to using new materials are usually worthwhile.

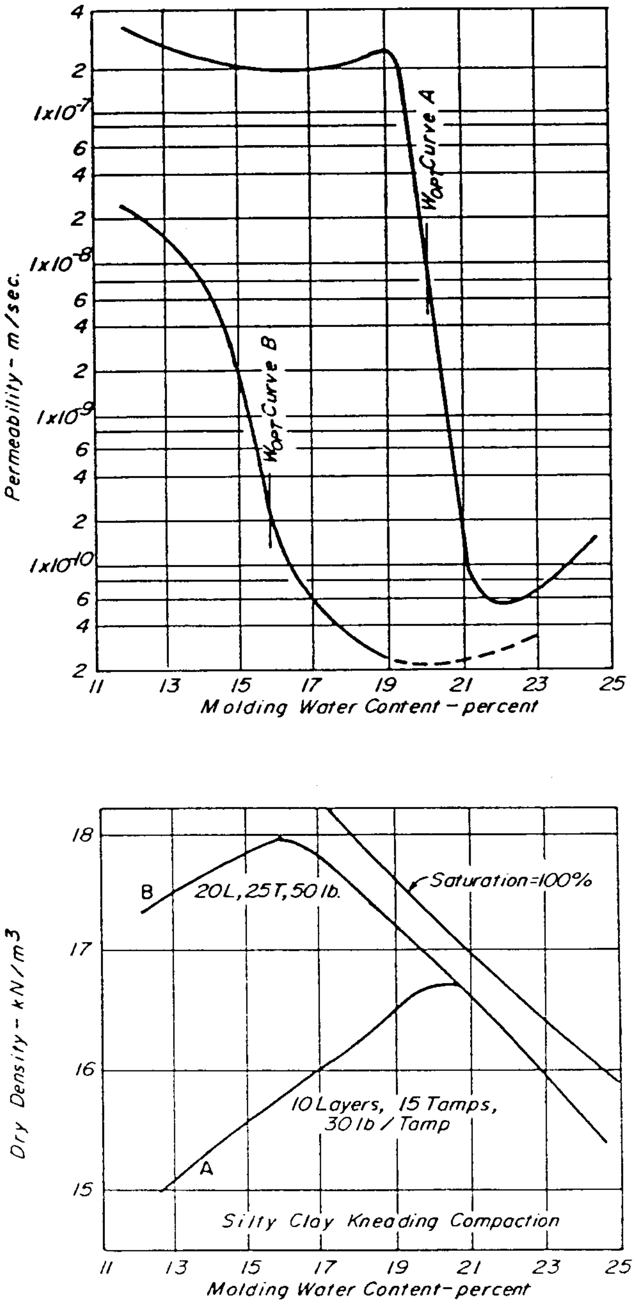

Fig. 1 Effect of compaction on permeability

Provided that low permeability is achieved, the dominant mode of transport in subsequent field operations is likely to be by diffusion. Such diffusion quite often results in a further decrease in permeability as a result of chemical precipitation and biological activity in the clay.

3.1.3 Thin Clay Membranes

A new breed of clay liners has appeared on the scene in recent years. These are sometimes referred to as Geosynthetic Clay Liners (GCL), see Daniel (1991). They consist of a thin, approximately 10 mm, layer of sodium bentonite sandwiched between geotextiles or glued to a geomembrane. The four GCL liners currently manufactured are Claymax®, Bentomat®, Bentofix®, and Gundseal. The liners provide about 5 kg/m^2 of bentonite. They are manufactured in rolls 4 m to 5 m wide and are easy to instal. The bentonite is dry on placement, and it is hydrated after installation. Sealing at joints is effected by overlapping. Under laboratory conditions, permeabilities of about 1 x 10^{-11}m/s are reported.

They are said to outperform compacted clay liners two orders of magnitude thicker, but with permeabilities also two orders higher. While this may be true in some instances, we question the toughness of such a thin liner, especially since it can obviously be subjected to very high hydraulic gradients. They also have less leachate attenuation capacity than the much thicker CCL.

A possible combination would be to place a GCL over a CCL. This would combine the advantages of both a degree of redundancy and the advantage of material compatibility, i.e. clay to clay.

3.1.4 Slurry Trench Cutoffs

The use of bentonite and cement bentonite vertical cutoff trenches for seepage barrier walls has been around for 30 years or so. They have been used for prevention of underseepage beneath dams and for the isolation of buried waste where contamination of adjacent groundwater is a concern.

In their simplest form they can be excavated to shallow depths with backhoe equipment and backfilled with the native soil conditioned with bentonite. Walls of depths up to 30 m are excavated with special clamshell equipment . Thicknesses of walls are usually about 1 m. Under saltwater conditions, attapulgite replaces high swelling sodium bentonite. By their nature, all such walls are backfilled with material that is necessarily uncompacted, relying for impermeability on the high swelling property of the sodium montmorillonite clay mineral. In many instances they perform well, but there is no level of redundancy or line of defence. Thus, in a harsh chemical environment the clay mineral may deteriorate and yield to seepage flow of unacceptable quantities.

A slurry trench is similar to a puddle clay core and puddle clay filled cutoff trench that was used so extensively in Victorian water storage dams, particularly in England. Puddle clay, in fact, dates back to the 18th century where it was used for the lining of the early canals. Soft wet clay was tramped on repeatedly by labourers in boots until the material was worked into a uniform cohesive paste filling all the voids, chinks and crevices. Modern slurry trench construction has been used to repair some of the early dams and also some of the not so early dams. Bentonite, cement and aggregate slurry backfills are sometimes referred to as plastic concrete. Very thin, vertical, cement bentonite curtains have been installed using the vibrated beam method in what is, in effect, a grouting technique, see Leonards et al (1985). Slurry trench cutoff walls for control of groundwater impeding lateral flow are described by Xanthakos (1979). A modern treatment of the subject of clay core dams was dealt with very fully at a conference held in London, England, see ICE (1989).

3.2 Flexible Membrane Liners

Geomembranes or Flexible Membrane Liners (FML) that are used as impermeable liquid or vapour barriers are usually made from continuous polymeric sheets that are very flexible, but could also be made from the impregnation of geotextiles with asphalt as elastomer sprays. For the purpose of this paper it is intended to discuss only, continuous polymeric sheet geomembranes.

Geomembranes are not absolutely impermeable (actually nothing is), but they are relatively impermeable when compared to geotextiles or soils, or even clay soils. Some typical values of permeability, as measured by water vapour transmission tests, are in the range of 10^{-10} or 10^{-13} ft/min.

The primary function of FML's is to provide a barrier between hazardous and/or polluting substances and surrounding ground and groundwater, or as in the case of landfills, to provide a low permeability cover barrier to prevent the intrusion of rainwater into a closed landfill.

The large majority of FML's are thin sheets of flexible thermoplastic or thermoset polymeric materials. The most common of these materials used in the manufacture of FML's are discussed below.

The major flexible membrane liners used today are:

- Polyvinyl Chloride - PVC
- Chlorinated Polyethylene - CPE
- High Density Polyethylene - HDPE
- Chlorinated Sulfonated Polyethylene - CSPE
- Ethylene Interpolymer Alloy - EIA
- Very Low Density Polyethylene - VLDPE

PVC, CPE and CSPE are essentially non-crystalline amorphous products, which allow solvent or heat seaming, high puncture resistance, and high coefficients of friction. Additional strength is achieved when combined with reinforced scrims.

Polyvinyl Chloride (PVC) has been used longer than the other materials and has been the leading supplier to the containment industry over time. PVC's cost effectiveness has maintained its growth for non-hazardous applications. These applications include sanitary landfills, heap leaching, wastewater containment, impoundment closures, canals, and decorative ponds.

Chlorinated Polyethylene (CPE) is applicable to some hazardous as well as non-hazardous applications, primarily waste water impoundments and industrial landfills. The cost and availability of this product for environmental applications has resulted in a decreased overall market share. CPE is used for specialized containment applications and methane barriers.

High Density Polyethylene is an inert thermoplastic material, which is resistant to a wide range of chemicals. Its compatibility with most hazardous waste streams has resulted in its increasing use for hazardous waste landfills, surface impoundments, sanitary landfills and heap leaching. While polyethylenes must be heat seamed, it may be exposed to sunlight and is suitable for potable water.

Chlorosulfonated Polyethylene (CSPE) commonly known as Hypalon® is resistant to ozone, ultraviolet light, and most chemicals except those containing high concentrations of hydrocarbons or chlorinated solvents. It is available in industrial or potable water grade.

Ethylene Interpolymer Alloy (EIA) commonly known as XR-5®, is a woven polyester fabric coated with a polymer alloy, which exhibits good chemical resistance.

Reinforced EIA exhibits good dimensional stability and tensile strength and is used in many hazardous applications. It is used for floating covers, baffles, and containment booms. Unsupported EIA is available for applications requiring chemical resistance and high elongation properties.

Very Low Density Polyethylene (VLDPE) is a polyethylene that exhibits high elongation and puncture resistance and may be exposed to U.V. without degradation. It is used primarily for heap leaching, landfill caps and canal linings.

Several geomembrane composites have been developed using nonwoven geotextile laminated to PVC, hypalon, or polyethylene. Research is continuing on new material composite combinations.

FML's are produced in various forms:

- Single ply non-reinforced;
- Multiply geomembranes with one or more layers of reinforcing fabric scrim between the layers;
- A third production method is also in use where geomembranes are bonded with different kinds of geotextile or geonet to form a geocomposite liner. These additional layers are usually provided for strength, drainage or improvement of the interface friction capabilities;
- FML's can be produced to have either smooth or textured surfaces.

The various properties of these FML's and their material of construction can be grouped into categories as shown below, after Koerner (1990). Each of these properties plays an important and definitive part in the design and construction of containment facilities, and for this purpose some very detailed test methods have been developed and prescribed by organizations such as NSF, AST and CSA.

These properties can be grouped as:

- Physical:
  - Thickness, mass per unit area, water vapour transmission and solvent vapour transmission;
- Mechanical:
  - Tensile behaviour (dumbbell shape) (uniform width) (three-dimensional - axi-symmetrical)
  - Seam behaviour, tear resistance, impact resistance, puncture resistance, friction, anchorage, stress cracking;
- Chemical:
  - Swelling resistance, chemical resistance, ozone resistance, ultra-violet light resistance;
- Biological:
  - Resistance to animals, fungi and bacteria;
- Thermal:
  - Warm temperature behaviour;
  - Cold temperature behaviour;
  - Coefficient of thermal expansion.

3.3 Installation and QA/QC

The sheets are prefabricated to manageable sizes in the factory and shipped to the site where they are placed and final cutting and sizing is completed. The joining is carried out in the field by either heat welding or joining by solvent compound adhesive or fusion methods. In most cases the liners are shipped to site in 2 m rolls and then seamed in the field by one of the above methods.

Extensive AQ/AC procedures are carried out to ensure that all the above criteria are complied with, and that the field installation has been carried out in accordance with guidelines. Seam leak tests are carried out to ensure leak-free seams, but it is not possible to test the whole surface area of a liner system for leaks. As a result, most regulations allow a certain minimum leakage through liners, eg. the US. EPA-RCRA Subtitle "D" guidelines allow a permissible leakage rate of 1 gallons/acre/day.

For this purpose leak detection and drainage systems are installed below a containment facility.

3.3.1 Modes of FML Failure in Containments

If an FML fails, failure will occur in one of two ways:

- An increase in the permeability of the liner to the contained liquids and dissolved constituents; or
- A breach in the liner, which would allow free liquids to flow through the liners.

3.3.2 Types of Failure in FML's

These are discussed by Matrecon (1988).

- Changes in the Permeability Characteristics of an FML:
  - A significant increase in the permeability of an FML to the liquids and the dissolved constituents with which the FML is in contact could arise due to chemical incompatibility after prolonged exposure;
- Mechanical Failure:
  - Puncture - Breaches in an FML can occur due to puncture by impact of tools or sharp objects such as rocks falling, or by sharp angular rocks in the subgrade that have become exposed because soil fines have migrated downward over time, or because of inadequate subgrade preparations or selection of cover materials. Puncture during operations, by man or vehicle, can largely be mitigated through good installation and operation procedure. Burrowing animals can puncture FML's below the surface and hoofed animals seeking water can puncture exposed liners;
  - Tear damage is similar to puncture damage but can be initiated by a puncture followed by stress at the hole. Tear, like puncture, can occur due to operations or animals;

- Cracks - Cracks can develop when an FML is simultaneously exposed to environmental stresses (eg. ozone, sunlight, or a waste liquid) and mechanical stresses. For example, cracks can develop in an FML exposed on a berm and in exposed areas with folds. Cracking can also develop from static stress and dynamic fatigue such as might occur with alternating thermal expansion and contraction. As with punctures, these cracks can initiate tears that can result in failure;

- Abrasion - The continuous action of water such as wave action, wind carrying sand particles, can cause the material to wear away and fail;

- Seam Failure - Factory and field seams can split open due to inadequate adhesion and due to excessive stresses on the FML, which can arise from subsidence, wind and wave action, gas pressure underneath the containment that has not been properly vented, shrinkage, hydrostatic pressure, slope sloughing, and thermal expansion and contractions. Seams can fail due to absorption of organics by the adhesive, or the entrance of organics into the interface between the sheets of FML that were seamed.

3.3.3 Composite Flexible Membrane Liner Systems

Because of the ease with which FML's can be placed in conjunction with other geosynthetic products such as woven and non-woven geotextiles and geogrids, FML's are rarely used in isolation and are often placed in layers to provide extra strength, protection from physical damage, drainage or leak detection to the containment. Where more secure containment may be desirable, multiple layers of the above liner and geonet/geotextile composite may be placed in layers to provide additional security, drainage facilities, venting or limited leak detection.

3.3.4 High Security Vacuum Testable Liner Systems

In instances where security against leaks through a liner system is desirable, a new system has been developed that allows testing for leaks during construction and after the lined facility has been taken into use.

The Robertson Barrier Liner (RBL) is a patented, double, flexible liner system which permits the liner to be tested during installation, commissioning, operation and after facility closure, to demonstrate the presence or absence of leaks in the liner. The system may be used to monitor continuously for the onset of leaks and can indicate whether the leak is getting worse or is stable. It may also be used to prevent the escape of contained fluid in the eventuality that small leaks do develop.

An RBL consists of a sandwich of two layers of geomembrane on either side of a permeable zone, see Figure 2. The permeable zone is formed with a layer of geonet or by coarse texturing on the inner face of one of the membranes. The geomembranes are sealed along the outer edges of the sandwich, to form a cell. Drainage tubes are connected to the permeable zone at the lowest point to allow any fluids draining into the permeable space to be removed. A partial vacuum is applied to the permeable space through the drainage tube.

The partial vacuum causes an inward hydraulic gradient through both geomembranes. The inward flow of fluid or air indicates the presence of leaks and can be monitored by measuring the vacuum pressure. By maintaining a partial vacuum in the presence of leaks it is possible to maintain the inward gradient across the lower liner, and hence prevent the outward flow or "escape" of any fluids that may have entered the permeable space through the upper membrane.

The liner at a facility may consist of one or more cells. During liner installation each cell is tested after it is installed. Leaks are located and repaired before the liner is covered. The entire liner can be tested on commissioning to demonstrate that it is leak free, and has not been damaged during subsequent covering or additional construction. The owner is able to perform periodic or continuous checks to determine if the liners remain leak free. Such testing may be continued after the facility use is discontinued to demonstrate the long-term effectiveness of the liner system. Independent

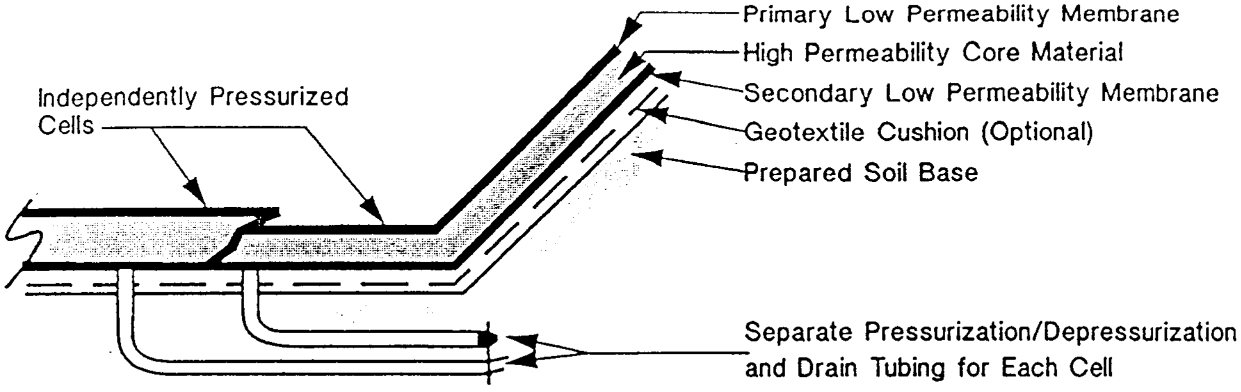

Fig. 2 Section through a portion of a typical Robertson Barrier Liner System

checks and verification by regulatory authorities are possible.

This liner system provides unprecedented security and reductions in risk of leakage and unprecedented environmental protection.

4.0 COMPOSITE BARRIERS

Because of the problems that can arise with both clay barriers and geosynthetic barriers, it is hardly surprising that the two are often combined for security reasons to provide a level of redundancy. A compacted clay liner may be incorporated as a backup to a geosynthetic. This is a "belt and braces" approach to containment. If the geologic environment is itself moderately secure, then three lines of defence can be utilized, the natural soil barrier plus two levels of artificial barrier. Multiplicity alone, however, is no guarantee for success.

Basnett and Brungard (1992) describe problems with desiccation of clay, in connection with expansion of a landfill, where a 60-mil HDPE geomembrane overlay 300 mm of compacted clay. On removal of the geomembrane the clay was found to be highly desiccated with cracks averaging 12 to 25 mm wide extending the full thickness of the clay. The desiccation occurred on the side slopes, the base being undamaged. Initial compaction was good with rigid QA/QC, and low measured permeabilities. The damage was thought to be a function of temperature with relative humidity fluctuations. It points to the need for adequate protective insulating soil covers on top of FML/CCL composites.

Another instructive case history is the failure in 1988 of the Kettleman Hills landfill liner in California. This is analyzed by Mitchell et al (1990). The liner was a composite FML on CCL double liner system, as mandated by RCRA. Slippage occurred on 1 on 2 side slopes, with lateral waste displacements of up to 11 m and settlements of up to 4.3 m during the course of a few hours. Surface cracking and tears in the liner occurred. Sliding occurred in the clay and FML interfaces. Liner interface friction angles as low as 8° were measured in laboratory tests. While instability could be avoided by filling repositories uniformly from the bottom, this is generally impractical for economic and operational reasons. Furthermore the use of very flat side slopes uses up too much volume. Very careful stability analyses therefore need to be carried out in order to develop safe filling operations. Seismic loadings also need to be considered.

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APPENDIX B

Records of Boreholes

<u>PACIFIC BENTONITE LIMITED</u>

Drilling Investigations on Hat Creek Claims - 1992

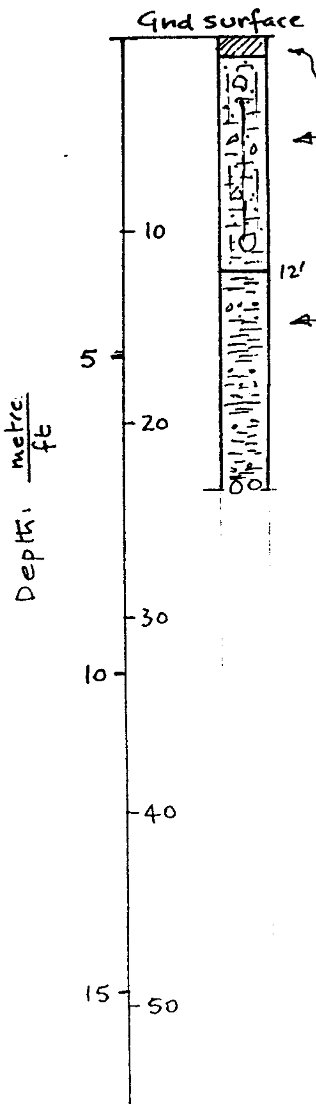
Record of Boreholes

Equipment : HT-1000 Top Drive Rig, with 114 mm continuous hollow stem auger.
Driller - Richard Diggle } Foundex Explorations, Surrey, B.C.
Helper - Dwain John }

N.B. Part-time drilling direction on techniques by Dennis Diggle, President of Foundex.

Supervision : Nigel A. Skermer, P.Eng. Consulting Engineer.

Borehole: 92-1



Topsoil (12")

Glacial Fill : very clayey, grey-brown with sand and gravel. Rough augering

Clay : Yellow-brown, bentonitic, with some fine gravel seams. Augering beyond 20' very tight.

Refusal on cobble at 23½'.

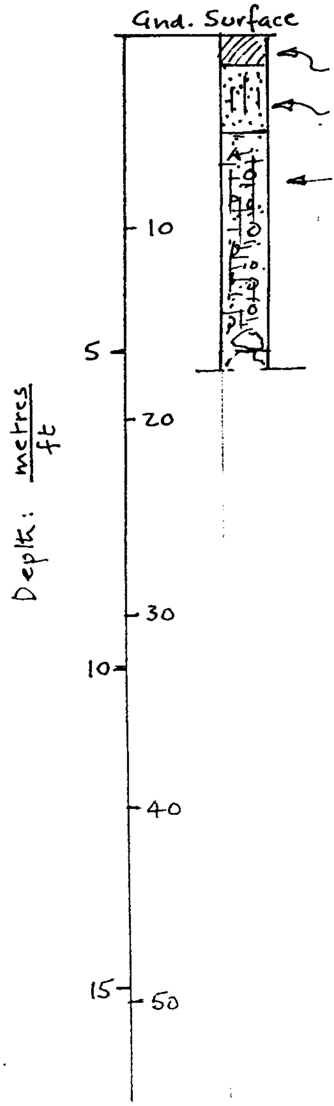
Hole dry.

Standpipe piezometer installed. Tip set 22-23½'.

N.B. Till, very tight and low permeability

Drilled: Sept. 29.

Borehole: 92-2



Topsoil (18")

Brown Silty Sand

Glacial Till : Grey-brown, very dense clayey, with sand, gravel, cobbles.

Refusal on cobble or boulder at 17'.

Hole dry.

First attempt at drilling met refusal at 7'. Moved over and redrilled.

Standpipe piezometer installed. Tip set 15'.

Drilled: Sept. 29.

Notes : For location of boreholes, see Figure 5.
Holes drilled September 29 & 30, 1992.

N.A. Skermer, P.Eng.
1 October, 1992

PACIFIC BENTONITE LIMITED

Drilling Investigations on Hat Creek Claims - 1992

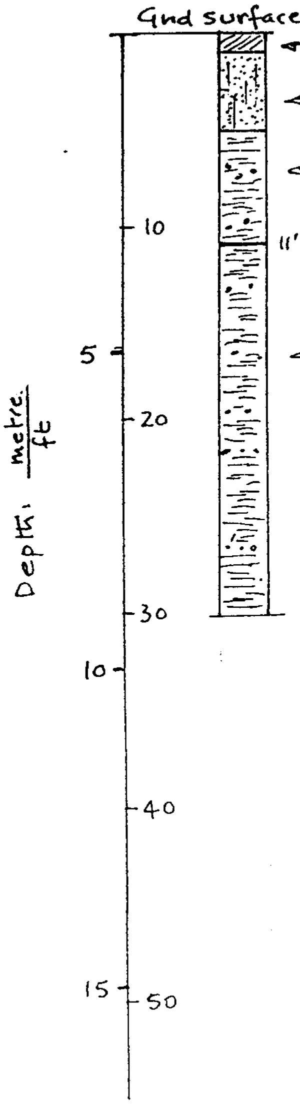
Record of Boreholes

Equipment : HT-1000 Top Drive Rig, with 114 mm continuous hollow stem auger.
Driller - Richard Diggle } Foundex Explorations, Surrey, B.C.
Helper - Dwain John }

N.B. Part-time drilling direction on techniques by Dennis Diggle, President of Foundex.

Supervision : Nigel A. Skermer, P.Eng. Consulting Engineer.

Borehole: 92-3A



Topsoil

Brown Silty Sand

Clay: Yellow-brown bentonitic, with some fine gravel. Oxidized clay

Clay: Blue-grey bentonitic with some fine gravel. Unoxidized Clay.

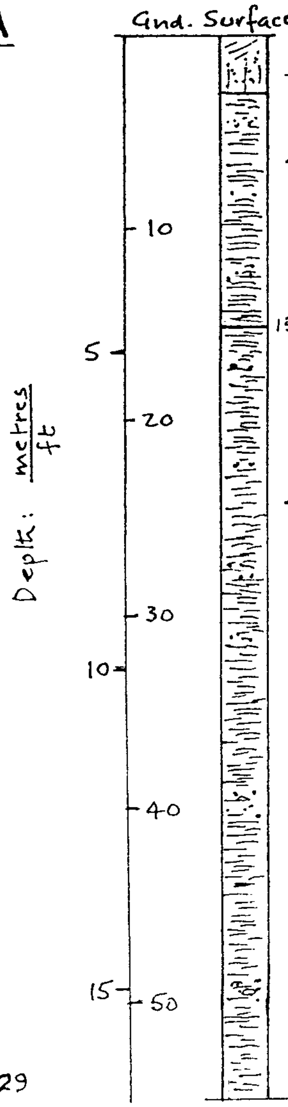
Refusal at 30', too stiff, and fearful off shearing off auger.

Saturated ground below 17'. Water rose to ground surface when auger removed.

Standpipe piezometer installed. Tip set 28½-30'

Drilled: Sept. 29

Borehole: 92-3B



Topsoil & Silty Sand

Clay : Yellow-brown bentonitic, with some fine gravel. Oxidized clay.

Clay. Blue-grey bentonitic with some gravelly seams. Rig action indicates gravel seams.

Drilling becoming harder with depth

Saturated ground below 20'.

No standpipe piezometer installed

Stopped at 55'. Could possibly have drilled deeper, but rig or auger may have broken.

Drilled: Sept. 29.

Notes : For location of boreholes, see Figure 5.
Holes drilled September 29 & 30, 1992.

N.A. Skermer, P.Eng.
1 October, 1992

PACIFIC BENTONITE LIMITED

Drilling Investigations on Hat Creek Claims - 1992

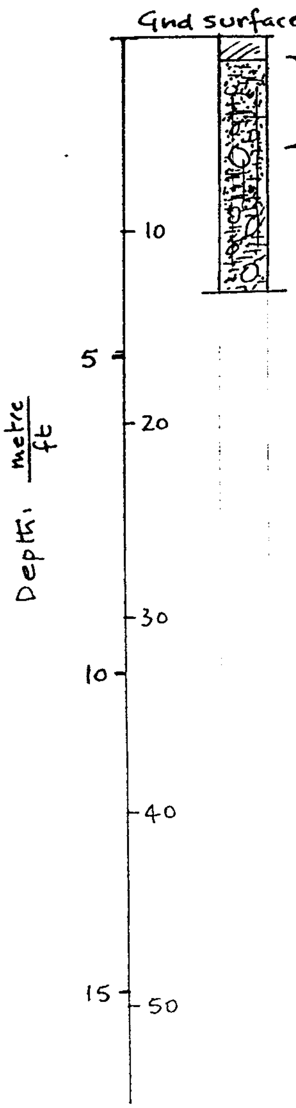
Record of Boreholes

Equipment: HT-1000 Top Drive Rig, with 114 mm continuous hollow stem auger.
Driller - Richard Diggle } Foundex Explorations, Surrey, B.C.
Helper - Dwain John }

N.B. Part-time drilling direction on techniques by Dennis Diggle, President of Foundex.

Supervision: Nigel A. Skermer, P.Eng. Consulting Engineer.

Borehole: 92-4



Topsoil

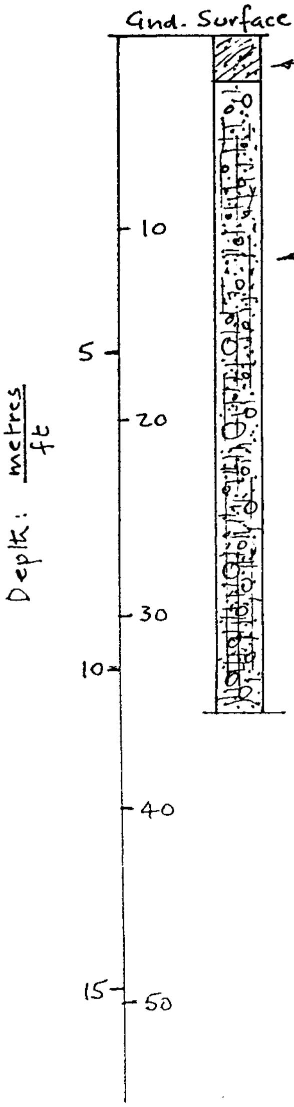
Glacial Till: Brown bentonitic till, but very gravelly with cobbles and boulders

Refusal at 13'. Made 3 attempts to drill at this location.

Hole dry, but standpipe piezometer installed. Tip set 7-9', hole caving.

Drilled: Sept. 30

Borehole: 92-5



Topsoil: Light brown, sandy (30")

Glacial Till: Brown, becoming blue-grey with depth, dense clayey gravelly with cobbles. (Possibly conglomerate, but erratics suggest till). Very hard, slow drilling.

Refusal on cobble at 35'

Hole dry.
Standpipe piezometer installed. Tip set 27-29'

Drilled: Sept. 30.

Notes: For location of boreholes, see Figure 5.
Holes drilled September 29 & 30, 1992.

N.A. Skermer, P.Eng.
1 October, 1992

PACIFIC BENTONITE LIMITED

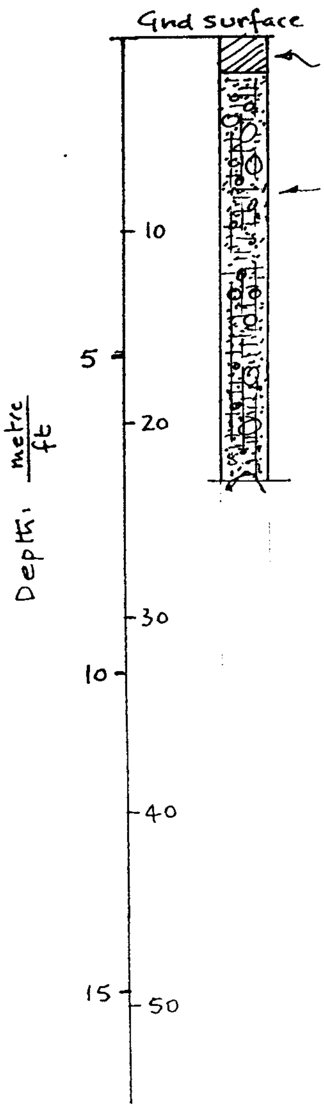
Drilling Investigations on Hat Creek Claims - 1992

Record of Boreholes

Equipment : HT-1000 Top Drive Rig, with 114 mm continuous hollow stem auger.
Driller - Richard Diggle } Foundex Explorations, Surrey, B.C.
Helper - Dwain John }
N.B. Part-time drilling direction on techniques by Dennis Diggle, President of Foundex.

Supervision : Nigel A. Skermer, P.Eng. Consulting Engineer.

Borehole: 92-6



Topsoil (24")

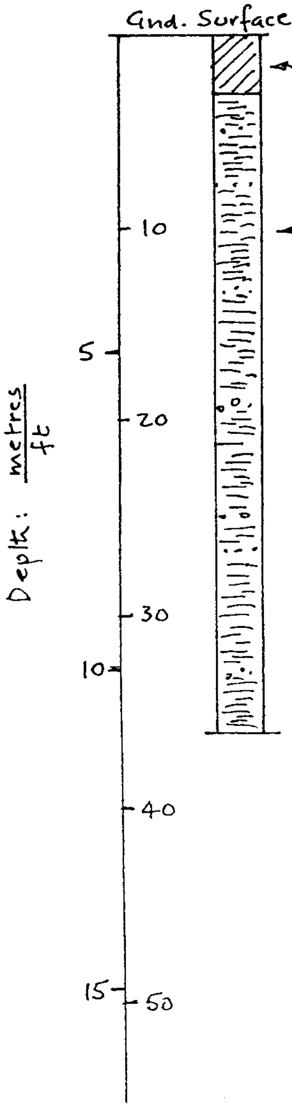
Glacial Till: Brown clayey, sandy with gravel and occassional cobbles/ boulders.

Refusal at 23'. Drilled hole 3 times, each time hitting boulder.

Hole dry, but no standpipe piezometer installed.

Drilled : Sept. 30.

Borehole: 92-7



Topsoil (36") Boulderey

Clay: Yellow-brown, bentonitic clay. Very fat at surface

Some fine gravel seams (particles volcanic and limestone). Clay gradually becoming blue-grey with depth below about 20'

Generally very smooth drilling.

Hole dry.

Stopped at 36'. Ground too hard to drill deeper with this rig.

Moved rig once because of bouldery surface. Redrilled.

Standpipe piezometer installed. Tip set 15-17'

Drilled : Sept. 30.

Notes : For location of boreholes, see Figure 5.
Holes drilled September 29 & 30, 1992.

N.A. Skermer, P.Eng.
1 October, 1992

APPENDIX C

Costs Claimed - Detailed Invoices

(i) Foundex Explorations Ltd.

(ii) Nigel A. Skermer, Engineering Costs.

1295

FOUNDEX
EXPLORATIONS LTD.

14613 - 64th Avenue
Surrey, B.C. V3S 1X6

Tel. (604) 594-8333
Fax. (604) 594-1815

FILE COPY

INVOICE DATE	OCTOBER 2, 1992
OUR PROJECT No.	826
YOUR PROJECT No.	
EQUIPMENT	HT 1000 4X4

PACIFIC BENTONITE LTD.
c/o SRK B.C. LTD.
800 - 580 Hornby Street
Vancouver, B.C.
V6C 3B6

Attention: Mr. Nigel Skirmer, P. Eng.

Re: Drilling at Hat Creek, B.C. on September 28 to 30, 1992

1) Mobilization & Demobilization - lump sum		$3,500.00
2) Drilling - 19 hours @ $160.00 per hour		3,040.00
3) Overtime Adjustment - 3 hours @ $35.00 per hour		105.00
4) Crew Accomodations - 4 man days @ $80.00 per day		320.00
5) Consumables		
- 3 bentonite chips @ $19.50 each	58.50	
- 6 bags silica sand # $9.90 each	59.40	
- 200 ft 3/4" PVC pipe @ $.55 per ft.	110.00	227.90
SUB TOTAL		7,192.90
G.S.T. #R101857381		503.50
TOTAL:		$7,696.40

cc: ACCOUNTS PAYABLE

NET 30 DAYS FROM DATE OF INVOICE

N. A. SKERMER MSc MICE PEng
consulting engineer
geotechnics

6260 Nelson Avenue
West Vancouver, British Columbia
Canada V7W 2A5
Bus: (604) 681-4196 • Res: (604) 921-6969
Fax: (604) 687-5532

October 1, 1992

Pacific Bentonite Ltd.
1386 Main Street
North Vancouver, B.C.

A.	To consulting engineering, drilling investigation, planning, direction, supervision and borehole logging, including travel time:	
	31 hours $ $100/hour	$ 3,100.00
B.	Sampling of clay from Clay Cut in June 1992:	
	11 hours $ $100/hour	$ 1,100.00
C.	Preparation of report on assessment work for 1992 season:	
	14 hours $ $100/hour	$ 1,400.00
	Travel expenses - 768km $ 30¢/km	$ 230.04
	Miscellaneous meals	$ 50.00
	Photocopies	$ 30.00
	Note: Hotel expenses for Nigel A. Skermer in September picked up by Foundex.	$ 5,910.04
	Goods and Services Tax of 7%:	$ 413.70
	Total:	$ 6,323.74

N. A. SKERMER MSc MICE PEng
consulting engineer
geotechnics

6260 Nelson Avenue
West Vancouver, British Columbia
Canada V7W 2A5
Bus: (604) 681-4196 • Res: (604) 921-6969
Fax: (604) 687-5532

October 5, 1992

Pacific Bentonite Ltd.
1386 Main Street
North Vancouver, B.C.

To consulting engineering for laboratory testing of bentonite for permeability and cation exchange:

17 hours at $100/hr	$ 1,700.00
Goods and Services Tax of 7%	$ 119.00
Total:	$ 1,819.00

NIGEL A. SKERMER
Corporate Consultant

Education	Victoria University of Manchester, England B.Sc. Civil Engineering, 1960 M.Sc. Soil Mechanics, 1963
Affiliations	Canadian Geotechnical Society Vancouver Geotechnical Society
Registrations	Association of Professional Engineers and Geoscientists of British Columbia Member of Institution of Civil Engineers, London, England Member of American Society of Civil Engineers, New York

Experience

1989 - Present	**Corporate Consultant, Steffen Robertson and Kirsten (B.C.) Inc.** Geotechnical aspects, including lake dredging for large fill, Green Lakes Golf Course Development, Whistler, B.C. Guidelines for tailings and waste rock management, US Bureau of Mines, Alaska. Research into geotechnical and commercial uses of local B.C. bentonite clays. Project Manager for 104 m roller compacted concrete tailings dam for Echo Bay Mines, AJ Gold Project, Juneau, Alaska. Expert witness for BC Hydro for large highway culvert destroyed by debris flood near Revelstoke, B.C. Expert witness for BC Rail for large landslide in embankment near Williams Lake, B.C. Investigation of various local landslides following torrential fall rains.
1987 - 1989	**Associate Consultant to Steffen Robertson and Kirsten (B.C.) Inc.** Tailings dams, waste dumps and mill foundations for gold mines in B.C., Yukon and Alaska. Preparation of manual for National Uranium Tailings Program. Debris flow investigations related to logging practices in Southwestern B.C. Evaluation of geotechnical hazards on Fitzsimmons Creek for Resort Municipality of Whistler.
1984 - 1987	**Geotechnical Consultant, Vancouver, Canada** Construction of cement grouted ground anchors in permafrost on Baffin Island, NWT. Foundation investigations in Surrey, B.C. for Vancouver Rapid Transit. Investigations of road pavement failures at SFU. Advice to residents on creek control works at Lions Bay, Cypress Creek, West Vancouver and Whistler, B.C. Litigation on fill settlement, Burnaby. Litigation on M Creek and Alberta Creek debris flows. Construction of coal stockpile platform, BP Coal Australia, Hunter Valley, NSW, feasibility studies open pit coal mine, Oaklands, NSW and design of small earth dams using dispersive clays, Sydney, Australia.
1982 - 1984	**Senior Geotechnical Engineer, Golder Associates, England** Repairs to canal tunnel linings and foundations; Welsh slate quarry backfill studies; shaft excavation dewatering; contractual claims; sewer investigations; evaluation for B.C. Coroner's Service of Alberta Creek debris flow, 1983.

1977 - 1982 **Geotechnical Consultant, Vancouver, Canada**

Consultant to Golder Associates, Sigma Engineering, B.C. Hydro & Power Authority, B.C. Uranium Commission and B.C. Coroner's Service.

- Mining pit slope stability and waste disposal; land development for residential schemes and roads; offshore engineering. Landslide investigations, both mountain rock slides and debris flows. Litigation aspects of landslides.
- From 1974 to 1982 involved with all geotechnical aspects of B.C. Hydro's 2000 MW Hat Creek Coal project, including site investigations, pit slope stability, waste disposal dumps, creek diversion, and studies for cooling water supply pipeline and intake structure.
- Since early 1981, major involvement on the design of a sand filled Mobile Arctic Caisson for Beaufort Sea oil exploration for Gulf Canada Resources. Evaluated liquefaction potential of caisson sandfill to withstand large pulsating forces from the wind driven arctic pack ice; involved centrifuge model testing of caisson at Manchester University, England with P.W. Rowe.
- Other work included geotechnical studies for:
  - impact of collapse of Barrier, a large cliff of volcanic rock at Garibaldi on Daisy Lake Reservoir for B.C. Hydro;
  - evaluation of ground conditions, including slides in marine clays for townsite development for AMAX molybdenum mine at Kitsault, B.C.;
  - development studies for Panorama Ski Village in the Kootenays, B.C.;
  - advice to attorneys at B.C. Uranium Commission hearings; and
  - B.C. Coroner's Service of M Creek debris flow, 1981 and Squamish highway rockfall, 1982.
- From 1976, historical research into landslides in the Alps.
- In 1977 chaired APEBC Committee on Natural Hazards

1974 - 1977 **Specialist Geotechnical Engineer, Golder Associates, Vancouver**

- Design and construction supervision of tailing dams and townsite foundation investigations at Cantung, NWT.
- Feasibility studies for tailing disposal, water supply, access road, airstrip and mill foundations for proposed AMAX tungsten mine at Mactung, NWT.
- Investigation of large submarine landslide at Kitimat Harbour, B.C., involving spontaneous liquefaction of sands, followed by litigation. Landslide studies for Canadian Pacific Railway. Feasibility studies for regional disposal of copper tailings for State of Minnesota, USA.
- Investigation of collapse of large super span metal culverts installed in frozen ground on Mackenzie Highway, NWT. Later redesign of culverts and field supervision of installation.
- Model studies of seepage through Climax Molybdenum tailing dam, Colorado, USA.

1965 - 1974 **CASECO Consultants (later Crippen Engineering), Vancouver**

Soil mechanics aspects of the design of Mica Dam for B.C. Hydro. Completed in 1973, the dam is a 243 m high earth dam. Work involved:

- Direction and supervision of laboratory tests on soils, including 1 m diameter triaxial tests on rockfill in the CFE cell in Mexico.

- Finite element analysis of El Infiernillo Dam in Mexico and Mica Dam to forecast stresses and displacements.
- Design and preparation of contract documents for instrumentation and details of dam embankment.
- On completion of dam, evaluation of instrumentation results and further finite element analyses using measured fill properties.

Feasibility studies including foundation drilling, seismic surveys and borrow search at dam site on McGregor River, B.C. and on Bear River, NWT. Design and testing of piled foundations and approach fills for new Pitt River Bridge, Coquitlam, B.C.

1962 - 1965 **Site Investigations and Foundation Engineer, Truscon, London and Subsoil Surveys, Manchester, England**

Site investigations, foundation engineering and mining subsidence studies for buildings, bridges and roads throughout the United Kingdom.

NIGEL SKERMER
PUBLICATIONS

Skermer, N.A., and Röhrs, R.G. "Natural and Artificial Barriers to Seepage." 2nd Int. Conf. on Environmental Issues and Management of Waste in Energy and Mineral Production, Calgary, Alberta, 1992.

Skermer, N.A., and Hungr, O. "Squamish Highway, Squamish - Whistler Areas." Tour Guide N°. 1, 1st Canadian Symposium on Geotechnique and Natural Hazards, Vancouver, B.C., 1992.

Skermer, N.A. and VanDine, D.F. "Catastrophic Impact of Some Historical Mountain Landslides". 1st Canadian Symposium on Geotechnique and Natural Hazards, BiTech Publishers, Vancouver, 1992.

Ward, P.R.B., Skermer, N.A. and LaCas, B.D. "The 50-year Flood in Fitzsimmons Creek, Whistler, British Columbia." 1st Canadian Symposium on Geotechnique and Natural Hazards, BiTech Publishers, Vancouver, 1992.

Johnson, D.J., Skermer, N.A. and Bergstrom, F.W. "Roller Compacted Concrete Tailing Retention Dam." Proc. Conf. Roller Compacted Concrete III, American Society of Civil Engineers, San Diego, 1992.

Ward, P.R.B., Skermer, N.A., and LaCas, B.D. "The 50-year Flood in Fitzsimmons Creek, Whistler, British Columbia, B.C. Professional Engineer, December 1991.

Byrne, P.M., Skermer, N.A. and Srithar, T. "Uplift Pressures due to Liquefaction of Sediments Stored behind Concrete Dams". 3rd Annual Conference, Canadian Dam Safety Association, Whistler, B.C. 1991.

Byrne, P. and Skermer, N.A. "Terremoto - Geotechnical Consequences". Special Issue - Earthquake Hazards in Southwestern B.C., with editorial by N.A. Skermer, B.C. Professional Engineer, April 1991. (Winner of Editorial Board Award for Best Article of 1991)

Skermer, N.A., Leslie, P.J., Johnson, D.L. and Reiss, J. "Roller Compacted Concrete Tailings Dam." 10th Canadian Hydrotechnical Conference, Canadian Society for Civil Engineering, Vancouver, 1991.

Skermer, N.A. "Landslides and Human Lives," translation of Bergsturz und Menschenleben, 1932 by Albert Heim. Bitech Publishers, 195 p., 1989.

Skermer, N.A. "Real Cheap Concrete Dams" B.C. Prof. Engineer, December, 1989.

Robertson, A. MacG. and Skermer, N.A. "Design Considerations for the Long-Term Stability of Mine Wastes". 1st International Environmental Workshop, Australian Mining Industry Council, Darwin, 1988.

Skermer, N.A. and Russell, S.O. "28th of October". B.C. Prof. Engineer, May, 1988 (Winner Editorial Board Award for best article of 1988).

Robertson, A.MacG., Knapp, R.A., Melis, L.A., and Skermer, N.A. 1987. Canadian Uranium Mill Waste Disposal Technology. NUTP, CANMET, Ottawa, Ontario, 308 p.

Skermer, N.A. "Pennies from Heaven". B.C. Prof. Engineer. May, 1987.

Skermer, N.A. and Kast, G. "DEWline Anchors in Permafrost". Geotechnical News, Vol. 4, No. 4, December, 1986.

Skermer, N.A. "Control Works for Debris Flows", Geological Society of America, 85th Annual Meeting Cordilleran Section Abstracts, May 1985.

Skermer, N.A. "Climequakes", B.C. Prof. Engineer, September 1985.

Skermer, N.A. Discussion on Voight, et al. "Nature and Mechanics of the mount St. Helens rockslide - avalanche of 18 May 1980". Geotechnique, Vol. 35, 1985, pp. 357-362.

Skermer, N.A. "M Creek Debris Flow Disaster", 4th International Symposium on Landslides, Toronto, 1984.

Skermer, N.A. "R.B. Stanton and the Great Landslides of the 19th Century on the Thompson River - An Appreciation", Can. Geot. Soc. Newsletter, April 1982.

Shields, D.H. and Skermer, N.A. "The Need for Pore Pressure Information from Shear Tests", American Society for Testing and Materials, STP 740, 1981.

Skermer, N.A. "Mount St. Helens: Act of God and Acts of Men", B.C. Prof. Engineer. July, 1980.

Skermer, N.A. "Alpine Landslides - a lesson for British Columbia?", B.C. Prof. Engineer. Aug. 1980

Skermer, N.A. "Earthquakes, Avalanches, Landslides", B.C. Prof. Engineer, January 1976.

Skermer, N.A. "Idaho: Abutment Seepage Preceded Collapse", New Civil Engineer, June 10th, 1976 (Teton Dam).

Skermer, N.A. "Mica Dam Embankment Stress Analysis", American Society of Civil Engineers, GT3, 1975 and closure to discussion, GT11, 1976.

Skermer, N.A. "Canada's Big Grand Mica Dam", New Civil Engineer, May 23, 1974.

Skermer, N.A. "Finite Element Analysis of El Infiernillo Dam", Canadian Geotechnical Journal, Vol. 10, 1973.

Skermer, N.A. and Hillis, S.F. "Gradation and Shear Characteristics of Four Cohesionless Soils", Canadian Geotechnical Journal, Vol. 7, 1970.

Rowe, P.W., Oates, D.B. and Skermer, N.A. "The Stress Dilatancy Performance of Two Clays", American Society for Testing and Materials, STP No. 361, 1963.