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A Geotechnical Assessment of the Waterways Formation for Underground Mining

University — Université

University of Alberta

Degree for which thesis was presented — Grade pour lequel cette thèse fut présentée

Master of Science

Year this degree conferred — Année d'obtention de ce grade

1980

Name of Supervisor — Nom du directeur de thèse

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A Geotechnical Assessment of the Waterways Formation For Underground Mining

by

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A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF Masters of Science

Mineral Engineering

EDMONTON, ALBERTA

Spring 1980

THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled A Geotechnical Assessment of the Waterways Formation For Underground Mining submitted by Kevin A. Williams in partial fulfilment of the requirements for the degree of Masters of Science.

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ABSTRACT

The Waterways Formation directly underlies some 70% of the Athabasca Oil Sands deposit of northeastern Alberta. The major part of the Oil Sands of the McMurray Formation is too deeply buried for recovery by surface mining operations and must be won by in-situ, underground mining or hybrid in-situ/underground mining techniques. Various methods involving mining development in the overlying Clearwater Shales, within the Oil Sands themselves, or from within the Devonian strata beneath the Oil Sands have been proposed. The predominantly limestone strata of the Waterways Formation should provide superior ground conditions to those present in either the Clearwater shales or McMurray Oil Sands, and from openings in the limestone, various types of Oil Sand or bitumen recovery could be conducted, including block caving, hydraulic mining, in-situ recovery or combinations of these methods.

This report summarizes the results of research into the rock mechanics properties and ground conditions of the Waterways Formation. In addition to laboratory and field data collected as part of the research, an extensive literature survey gathered together much of the currently available data relating to the geology, hydrology and geotechnics of the Waterways Formation.

A number of outcrops along the Athabasca River and tributaries were selected for detailed examination of the jointing, bedding and lithologies of the Formation and for

collection of laboratory test samples. Core from a 31 metre deep drill hole at the Suncor mine provided numerous samples of fresh rock for laboratory testing and provided lithological and geotechnical information for a continuous, unweathered sequence of part of the Moberly Member strata.

On the basis of the field and laboratory work three basic types of limestone - Massive, Nodular and Shaly - have been identified with differing rock mechanics characteristics. Data on joint shear strecngths, jointing systems and geometries, and intact strength are used to make some preliminary estimates of the likely ground conditions at depth, rock support requirements, groundwater conditions and state of stress. Two separate chapters are devoted to karst and karsting in the Oil Sands region and to possible industrial uses for the Waterways Formation rocks.

Acknowledgements

I wish to thank those who have assisted in this study, especially the Alberta Oil Sands Technology and Research Authority (AOSTRA) who provided the major funding. I am grateful to AOSTRA for supporting this research and for permitting the results to be presented in a thesis.

I also extend my gratitude to Mr. Gene Sandford and Suncor Resources who provided a field site and support for a core hole in the Suncor mine.

I sincerely thank Dr. Brian Stimpson, my supervisor, for his guidance and cheerful encouragement. I would also like to thank Mr. Lin Ding for his careful help for much of the drafting, for laboratory services and for field assistance at Fort McMurray.

Many other people offered help and suggestions, in particular I would like to thank Professor Patching, Dr. Jeremic and Dr. Dusseault, all of the Department of Mineral Engineering. I thank Alberta Transport and Dr. P.K. Chatterji of Thurber Consultants who provided samples and test data, to Dr. Fritz Boehm of Krupp Industries, to PetroCanada, to Syncrude Canada, and to the Research Council of Alberta. To others who provided advice and help in many ways I add my gratitude.

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1. INTRODUCTION

The Athabasca Oil Sands deposit occurs in the McMurray Formation of Cretaceous age. Owing to the uncemented and porous nature of the McMurray Formation the sands have provided a reservoir for enormous volumes of migrating bitumen whose source remains uncertain. The total amount of bitumen in the deposit is not accurately known. The most recent and reliable estimates prepared by the Alberta Research Council (1978) place the total at about 800 billion barrels. Only a small part of this total, perhaps 10%, can be recovered by surface mining methods under present economic conditions. The remaining 90% will have to be won by some other method or combination of methods.

The Waterways Formation directly underlies a large part of the Athabasca Oil Sands of north-eastern Alberta (figure 1) where two large surface mines are currently in production - Suncor Oil Sands Division (formerly Great Canadian Oil Sands), operating since 1967, and Syncrude, operating since 1978. The Waterways Formation forms a strong and well defined floor at the Suncor mine, but not at Syncrude where barren or low grade Oil Sands separate the main oil sand horizon from the Waterways Formation. In other respects these strata have no significance for surface recovery of the estimated 75 billion barrels currently considered accessible by surface mining techniques. The consideration of underground mining of the deeper portions of the Oil Sands or of in-situ bitumen recovery from underground (the so called Mining Assisted In-Situ Processing - MAISP) clearly indicate a need to investigate the geotechnical properties and likely engineering behavior of the Waterways Formation.

1.1 Location, Access and Physical Extent

The Waterways Formation lies in northeastern Alberta (see map, figure 2). The main urban centre is the city of Fort McMurray (population 25,000) which is accessible from Edmonton and southern Alberta by paved highway (#63) and by the Northern Alberta Railroad which provides freight service from Edmonton. Scheduled passenger planes connect Fort McMurray with Edmonton. The two large surface Oil Sands mines are accessible from highway 63 north from Fort McMurray. Boats and barges navigate the Athabasca River from Fort McMurray downstream to Lake Athabasca. With small motor craft it is possible to travel upstream on both the Athabasca and the Clearwater Rivers from Fort McMurray and also to travel up some of the larger tributary rivers. Motor craft, floatplanes and helicopters can be chartered in Fort McMurray.

The cross-section of figure 3 shows that the Waterways Formation comprises a wedge of rock tilted to the west. In the central area and to the east the upper boundary of the Waterways Formation is an ancient erosional surface which dips southwestwards. In the west the upper boundary is formed by the overlying Cooking Lake Formation. The lower boundary, the contact with the Livock River/Slave Point Formation, dips southwestward where it becomes deeply buried.

The upper boundary has been exposed by recent erosion by the Athabasca and Clearwater River systems. Outcrops of Waterways Formation rocks occur along the bottoms of the valleys of these rivers and for short distances along several of their larger tributaries (figure 2). Most of these outcrops are accessible only by boat although ten or more can be reached by road or by hiking. Away from the valleys of the two major rivers the Waterways Formation becomes covered by an increasing thickness of overburden.

To the east of the Athabasca River the Waterways Formation dips southwest at about 0.65 metres per kilometre, but the land rises towards Muskeg Mountain so that overburden can attain a thickness of of 250 metres or more. To the west of the Athabasca River the land rises towards the Thickwood Hills and Birch Mountain. In township 94-14 the surface of the Waterways Formation is already buried by 200 metres of material. Further southwest, where formation dips are about 4.5 metres per kilometre, it becomes even more deeply buried. South of Fort McMurray the overburden attains a thickness of 480 metres at the southern boundary of the Oil Sands Area.

1.2 Purpose of Evaluation of the Waterways Formation

Underground mining of Oil Sands could proceed in two ways: removal of Oil Sands as ore, or bitumen removal by in-situ recovery. Mine development could be within the McMurray Formation Oil Sands or it could be in the more competent and more easily supportable limestone strata of the Waterways Formation. Mine development for in-situ recovery of bitumen could also be advantageously placed in the Waterways Formation. Hybrid schemes involving development of underground in-situ recovery methods are known as Mine Assisted In-Situ Processing (MAISP) projects. MAISP operations could be carried out from the Waterways Formation below the Oil Sands, from the McMurray Formation itself, or from within the overlying Clearwater Formation. In-situ recovery from the surface using boreholes has been extensively field tested by oil companies and may at this time be feasible for large commercial projects. In-situ recovery from underground working places has not been tested and neither the technical nor the economic feasibility has been established. Figure 4 lists some of the recovery methods that have been proposed and summarizes the use that each could make of the Waterways Formation.

Only Method 3, surface mining, is producing commercially. Underground mining of the plastically-behaving Oil Sands has not yet been proven to be technically feasible or economic.

In-situ recovery methods under investigation employ holes drilled from the surface in an attempt to mobilize the bitumen by injection of various solvents or steam, or by in-situ combustion. Mobilization of bitumen of 8 degrees API viscosity is difficult and recoveries are low (in the order of 5 to 15%).

Mining development within the Waterways Formation is considered easier and safer than excavation in the McMurray Formation because of the greater stability of tunnels in the strong and durable Waterways limestones (Hardy and Hatch, 1977). In-situ recovery techniques from underground are speculated to be more efficient than surface in-situ methods because of shorter injection holes and less heat loss. Figure 5 illustrates several of the recovery methods that have been suggested. Three MAISP and mining projects (numbers 3, 4 and 8; mining, in-situ and mining/in-situ) will require extensive operations in the Waterways Formation, including a large amount of tunneling, and driving of raise-bores, ore chutes, haulageways and other mining works for underground mining or excavation of drilling chambers for in-situ operations. Oil sand mining or MAISP projects from within the underlying Waterways Formation limestones or from the overlying Clearwater Formation shales may provide a way of applying mining and petroleum recovery technology to winning of this vast resource at depths below those economically mineable by surface methods.

A general evaluation of geology, structure, and mechanical properties of the Waterways Formation is therefore desirable and is the goal of this report. More detailed knowledge of intact and rock mass strengths, mechanical behaviour under stress, modes of failure and groundwater hydrology of these strata will, of course, be necessary for any site that may be selected for mining or MAISP projects within the Waterways Formation.

1.3 Scope of the Geotechnical Evaluation

This report is a synthesis of currently available information on the Waterways Formation (that available in the public domain) and the results of the author's work. It provides a preliminary evaluation of the Formation for purposes of underground excavation and mine development.

The area of Waterways Formation subcrop beneath the McMurray Oil Sand Formation, the area with which this report is concerned, is about 22000 square km. The Waterways Formation subcrops beneath the eastern part (70% in all) of the Athabasca Oil Sands while stratigraphically higher Upper Devonian formations subcrop beneath the western half of the Oil Sands. Field data obtained in this study and that from previous investigations have been collected from only a few widely spaced locations. At most of these locations the data comes from the upper part of the Formation only. This upper zone has been influenced by weathering occurring adjacent to the ancient and/or the present erosional surface, thus there is no assurance that rock characteristics encountered at depth in a mine will be the same as those described in this study.

Available literature, in both published and unpublished reports and papers, comprises numerous lithological sections and stratigraphic and geological structural data as well as joint surveys, groundwater studies and a number of brief geotechnical appraisals.

The field and laboratory rock mechanics studies carried out for this report confirm and augment previously collected data. This study, which was conducted between April 1978 and September 1979, comprised the following:

1) a literature survey and collection of published and unpublished data
2) geological and geotechnical description of four outcrops of the Waterways Formation
3) collection of core and block samples
4) drilling a vertical core hole 31 metres deep into the Waterways Formation at the Suncor mine
5) rock mechanics testing (primarily laboratory work) of Waterways Formation rocks.

2. CURRENT GEOLOGICAL AND ENGINEERING KNOWLEDGE OF THE WATERWAYS FORMATION

This chapter presents a summary of information obtained from the literature concerning the geology, structure and geotechnical features of the Waterways Formation. Further information, obtained in this study, is presented in chapters three, four and five.

2.1 General Geology

The Waterways Formation was first described by Richardson in 1819 and 1825 from low outcrops along the Athabasca and Clearwater Rivers, where its stratigraphic position was readily observed beneath the McMurray Formation bituminous sands. Bell, in 1884, recognized that an erosional unconformity separated the two formations. Wells drilled for salt and for oil in this region permitted description and subdivision of the complete section of the Waterways Formation and correlation both locally and across western Canada. Figure 6 shows the names and locations of many of the exploration holes which have provided lengthy core intersections or stratigraphic information from the Waterways Formation. Warren (1933) was the first to apply the name Waterways Formation to those Devonian Rocks in the Fort McMurray region which overlie the Middle Devonian Prairie Evaporite evaporitic sequence. The Alberta

Government Salt Well No. 1 at Fort McMurray (1920) encountered 123.5 metres of Waterways Formation, although pre-Cretaceous erosion reduces the total thickness in this area. Seventy seven kilometres west-southwest, the entire sequence is preserved in the well Bear Biltmore No. 1. Crickmay (1957) established this 214 metre Bear Biltmore No. 1 sequence of Waterways Formation as a standard and defined its five members. All of the outcrops of the Waterways Formation along the Clearwater and Athabasca Rivers were described and compiled in a composite geological section by Norris (1963). Lithological descriptions of the Waterways Formation and of each of its five members are given by Norris (1963 and 1973).

Current geological knowledge is therefore based on information from widely scattered outcrops and from many drill holes. There are several thousand Oil Sands evaluation holes, most of which reach the upper part of the Devonian limestones. At least 50 exploration holes of oil companies have penetrated the entire Formation and have provided data in the literature on thickness and lithology of each member of the Formation. Of the evaluation and oil exploration holes which were cored into the Waterways Formation, the majority (perhaps as many as 100) reached only into the upper part of the Formation, and recovered incomplete core intersections. A list of Waterways Formation wells is given in Appendix A.

The following geological summary is drawn entirely from the reports of Norris (1963 and 1973). The Waterways Formation includes up to 214 metres of Upper Devonian limestone, shaly limestone and shale which lie on top of Middle Devonian limestone of the Slave Point Formation (see Figure 3). The lower contact of the Waterways Formation represents a period of non-deposition. The upper contact with the Upper Devonian Cooking Lake Formation limestone appears transitional. To the south of Fort McMurray, the Waterways Formation becomes less argillaceous and has been called the Beaverhill or Beaverhill Lake Formation. To the north and west the Waterways Formation becomes more shaly and has been correlated with Devonian shale units in the North West Territories. The general stratigraphy of the five members of the Formation from top to base is illustrated in figure 7. The interbedded nature of the Formation is exhibited on a large scale by the alternation of the members from dominantly shaly to dominantly limestone.

The Firebag Member is mainly olive green calcareous shales interbedded with thin and more resistant layers of olive green limestone. It is 51.8 metres thick in the type well (Bear Biltmore No. 1) and increases in thickness northeastwards to as much as 59.4 metres. There is a middle section between the upper and lower shaly intervals, varying in thickness from 6.1 to 30.5 metres, consisting mainly of limestone.

The Calumet Member is fine-grained clastic limestone, resistant in outcrop. The boundaries are well defined by shales of the Members above and below.

Lithologies described from outcrops by Norris (1963) include:

a. Hard, aphanitic, slightly brownish limestones that are thinly bedded

b. Highly fossiliferous, argillaceous, thin to thick beds of rubbly-weathering limestone with some interbeds of calcareous shale

c. Medium grey, fine grained, argillaceous limestone

d. Olive green shale with variable amounts of interbedded argillaceous limestone.

The thickness has only slight variation (without any apparent regional trend) from 27.7 metres to 31.1 metres.

The Christina Member is about 27.4 metres thick. It consists mainly of greenish grey shale, grey argillaceous limestone, pale brown aphanitic limestone and minor thickness of pale brown fragmental limestone. It appears to be more argillaceous and shaly to the north and west. Sandstone and sandy limestone beds, resulting from erosion of land of possibly restricted extent, outcrop near the mouth of the Christina River. Thickness of the Christina Member varies from 23.2 to 37.2 metres.

The Moberly Member, approximately 61 metres thick, consists dominantly of clastic limestones. It becomes more shaly towards the top and appears more shaly with thinning of limestone units to the north. Its lithology in ascending stratigraphic order (ascertained from well Bear Biltmore No.

1 and from outcrop.) is as follows:

a. Soft, grey, argillaceous limestones, light brown fine grained fossiliferous limestones, light grey resistant, aphanitic limestone, and thin bedded brownish limestone with calcareous shale partings

b. Alternating light green, rubbly, thinly interbedded limestones and shales, and hard, brownish aphanitic, fragmental limestone

c. Green variably calcareous shale, with thinner units of thin bedded argillaceous and fragmental limestones.

The Moberly Member outcrops discontinuously along the Clearwater River as far as 21 kilometres east of Fort McMurray, and along the Athabasca River from a point 25 kilometres southwest of Fort McMurray to Fort MacKay, 54 kilometres north of the city.

The Mildred Member is approximately 42.7 metres of grey calcareous shale, greenish grey argillaceous limestone and some brownish aphanitic, clastic limestone. There are few wells that penetrate the complete thickness of the Moberly and Mildred Members, and consequently there is sparse information on thickness variations.

In summary, the Waterways Formation is composed of five westerly dipping and conformable members, each of which subcrops beneath the McMurray Formation. The lowest member subcrops in the east and the upper member in the west. Outcrops of the Waterways Formation occur along some of the major rivers. The Firebag, Christina and Mildred Members are formed mostly of shale and shaly limestone while the intervening Calumet and Moberly Members are less shaly, having thick units of massive limestone in addition to shaly limestone.

2.2 Structure of the Waterways Formation

2.2.1 Regional Structure

The wedge of Waterways Formation strata thins to the east because the Devonian erosion surface truncates all of the Devonian strata which dip westerly at a steeper angle than the unconformity (see cross section, figure 3). Between the edge of the Canadian Shield in Saskatchewan and Fort McMurray the Precambrian basement dips westwards at about 3.5 metres per kilometre. In the vicinity of Fort McMurray, the dip of the base of the Waterways Formation is approximately 0.65 metres per kilometre to the west. Farther west this increases to approximately 4.2 metres per kilometre while the upper surface dips about 4.5 metres per kilometre southwest. The upper erosional surface of the Waterways Formation is frequently encountered during Oil Sands drilling and is therefore more accurately located than the base of the Formation. The upper surface is found to be quite irregular with relief of more than 100 metres. Relief on the Devonian limestone surface was present at the beginning of deposition of the McMurray Formation sands and resulted in thickening of the McMurray Formation in depressions on the Devonian surface. There may also be regional post-Cretaceous tilting to the southwest. Structure contour maps of the Devonian erosion surface have been made by Martin and Jamin (1963), PetroCanada, and the Alberta Research Council (in preparation).

Within the Waterways Formation there are basin and dome fold structures (plate 1). Carrigy (1959) favors the idea that the folds are a result of subsidence into underlying solution cavities in the Prairie Evaporite Formation, while Hume (1947) referred to the possibility that hydration and associated volume expansion of anhydrite beds could cause strata disruption. Maximum bedding dips in the folds are typically less than eight degrees, although dips as steep as 25 degrees have been observed (Dusseault, unpublished). The long axes of some elongate domes and the fold axes of most of the small folds trend south-southwest, suggesting that the origin of these structures is not related to the general westerly dip of the Devonian strata.

Although the scarcity of outcrops makes the identification of faults difficult, several large faults have been proposed (figure 8. Numbered faults on the map refer to numbers in the text following). Stewart (1963) suggests that block faulting in the Precambrian basement is reflected as ridges on the Devonian erosion surface, one of which (#1) runs north through the middle of the region. The McMurray Formation thins over these ridges and is low in bitumen content. Martin and Jamin (1963) state that many faults which affect only the Paleozoic and Precambrian appear to be striking northeastwards across the Oil Sands region. They noted one major northeast trending fault (#2) which offset erosional ridges on the Devonian surface. Carrigy (1959) positted a major fault (#3) running southeastwards from the Bitumount Basin (a structural basin 75 km north of Fort McMurray) towards a fault on the Clearwater River mentioned by Norris (1963). Norris concluded that there was about 70 metres of offset in the Methy Formation along a northwesterly trending normal fault downthrown to the west (#4). Hackbarth (1978) postulates the existence of a fault (#5) striking along the valley of the Athabasca River, from Fort MacKay south through Fort McMurray. He infers that the fault zone was sufficiently wide and permeable to promote more rapid solution and removal of salt from the Prairie Evaporite Formation and irregular subsidence of overlying strata. This fault would explain apparent offsets on the Precambrian surface and hydrogeological peculiarities in the area along the Athabasca River. Hackbarth did not specify the type of fault or displacement. Norris (1963) reported a minor fault (location unspecified) with about one metre of displacement, on the limb of a small fold in the Waterways Formation. The upper surface of the Prairie Evaporite Formation is presently as shallow as 130 metres below river level along the Athabasca River to the west of Fort McMurray.

2.2.2 Joint Systems

Jointing occurs throughout the Waterways Formation and has been studied by Babcock (1975), by Syncrude investigators (Sinha, 1976) and by others. Babcock's work (1975) is the most comprehensive. He suggests that there are two joint systems, each with two orthogonal joint sets. One system strikes north-south and east-west while the second strikes northeast-southwest and northwest-southeast. He found little variation of orientation within the sets at any one location and that not all joint sets are present at every outcrop. Babcock relates the origin of one of the joint systems to Cordilleran tectonic stresses.

Other researchers, with fewer data from less extensive joint surveys, have defined joint sets which are at variance with the sets of Babcock.

2.2.3 Solution Collapse Structures

Cavities in the Devonian surface have been interpreted as karst solution collapse structures, based on evidence from outcrops and on drilling data. Collapse features in the upper part of the Waterways Formation, from 50 metres to 15 kilometres across, appear to result from karst solution and cavern formation in underlying salt beds of the Prairie Evaporite Formation.

Collapse structures appear to be the largest and most extensive karst-produced feature in the Waterways Formation. In the Suncor and Syncrude mines, as well as near Fort

MacKay, drilling has delineated Oil Sand-filled cavities with steep to near vertical walls, 50 metres or more deep in the ancient erosional surface of the Waterways Formation. Near Bitumount there is a depression in the Waterways Formation erosional surface, known as the Bitumount Basin, which is 15 kilometres across with maximum relief of 120 metres. Outcrops of overlying Cretaceous strata are observed to have subsided into the depression. Karst, which is discussed in chapter 6, is able to cause serious problems for engineering construction underground and on the surface.

2.3 Geotechnical Information

Studies of geotechnical features have been conducted for specific engineering purposes in the Waterways Formation. Most of the investigations were conducted by consulting engineering companies on the Christina and Moberly Members. Figure 9 tabulates the types of studies conducted and some of the test results are presented in figure 10. As part of the foundation studies for the Suncor plant, rock samples collected from the outcropping shaly limestones were strength tested. The strata were found to provide an ample factor of safety against bearing capacity failure. However jointed and loosened blocks along the escarpment edge of the outcrop facing the Athabasca River required grouting to prevent horizontal movement.

Thurber Consulting conducted foundation evaluations of possible bridge crossings of the Athabasca River and as part of their investigations obtained some geological and rock mechanics data on the Waterways Formation bedrock. Shallow cores were obtained from Fort McMurray townsite and three other locations, 44, 49, and 54 kilometres north of Fort McMurray on the Athabasca River. Strength test results provided by Thurber Consulting and Alberta Transport have been incorporated into this report (Figure 10).

The cores taken at Fort McMurray, from the middle part of the Moberly Member, reveal a light creamy to grey colored, very hard limestone having some tar-filled fractures. Data obtained from the first and second locations along the Athabasca River are shown in figure 10. Lithology at the first and second locations consists mainly of limestone with "fractured grey shale and limestone". At the third location, near Fort MacKay, shallow coring and boring revealed 22 metres of limestone having thin shaly layers, underlain by 10 metres of shale. This is likely the uppermost part of the Christina Member. The series of test drillings near Fort MacKay encountered a cavity in the bedrock surface of unknown depth and of poorly defined lateral extent beneath the Athabasca River. The cavity is moderately large (depth >32 metres, width >40 metres) and could be a karst collapse structure. It is infilled with very stiff glacial clay.

Preliminary investigations for a MAISP (Mine Assisted In-Situ Processing) project being carried out by PetroCanada have involved rock mechanics testing of Waterways Formation strata. Lithologies, precise locations of contacts, and geotechnical characteristics were studied from cores and borings in the Moberly Member limestone (see figure 10). The test area is along the Waterways escarpment on the Athabasca River, east of the Syncrude mine.

Other investigations have included chemical analyses on shaly limestone of the Christina Member which confirmed its suitability for cement making, a number of joint surveys (discussed in section 2.2.2), and a recently released geotechnical study "Investigation of Waterways Formation Limestones" prepared by Golder Associates for the Canadian Centre for Mineral and Energy Technology (Canmet). Lithology logs provided by Thurber Consultants and Alberta Transport, by Hardy and Associates, and by EBA Engineering, as well as lithologs reproduced from Norris (1963 and 1973) are printed in Appendix A of Williams, Stimpson, Patching and Jeremic (1980).

3. PROJECT DATA - LITHOLOGY AND STRUCTURE

3.1 Acquisition of Data

The data for this project were obtained from several sources: a) from field work including geotechnical studies and sampling of outcrops b) from core logging and testing and c) from descriptions, data and test results recorded in the literature or provided by other investigators.

Geotechnical examination of four outcrops of the Moberly Member of the Waterways Formation included the folowing:

1) Lithological description of the exposed section
2) Sampling of each lithology for testing and more careful examination
3) Examination of bedding features
4) Joint line survey along the outcrop to collect data systematically on a large number of joints.

Core logging consisted of examination and description of cores from 18 widely separated core holes drilled for oil exploration, mining evaluation or geotechnical purposes. A large proportion of the lithologic and geotechnical data has been obtained from Carrigy (1959), Norris (1963 and 1973), Babcock (1975) and Hackbarth (1977 and 1978). All of these reports and papers provide descriptions of previous geological investigations and summarize the geology of the Waterways Formation. A detailed lithology and geotechnical log of core hole WW1 is presented in figure 11 (enclosed at end of report). Much of the detailed rock mechanics laboratory tests were conducted on core recovered from this hole (plate 2).

3.2 Description of Lithologies

Rock types in the Waterways Formation have historically been reported as being limestone, shaly limestone and shale. Based on examination for this study of several outcrops and of core from diverse areas and from all Members of the Formation, the lithologies are better classified by arranging them in the following three groups:

1. Massive Crystalline Limestone
2. Nodular Limestone
3. Shaly Limestone.

This simple grouping corresponds more accurately to lithologies encountered in the field and also to mechanical properties (plate 3). Within the three main rock groups several types will be defined. In addition, there are gradations between most of the types and these will be discussed. Figure 12 lists the major rock types and tabulates their distinguishing characteristics.

Before proceeding with a more detailed description of the types of the predominantly limestone rocks of the Waterways Formation, a summary of Folk's limestone classification used in this report will be given.

3.2.1 Limestone Classification

According to Folk (figure 13), limestones have the following constituents:

a) large fragments or crystals (allochems) and

b) fine crystals of calcite (orthochems).

The large fragments can be divided into fossils, pellets, oolites and intraclasts. Organic production of calcite shells during the life cycle is one of the most important processes of limestone formation. After death the organisms may be buried by other detritus and become fossil limestone rock.

Oolites are very distinctive spheres a few mm in diameter formed of chemically precipitated calcite. Pellets are tiny rounded grains 0.04 to 0.08 mm in size which have no ordered internal structure and are commonly of fecal or algal origin. Intraclasts are limestone fragments formed by erosion, either above or below sea level, of newly formed and poorly lithified limestone material.

Orthochems are generally formed non-organically by the precipitation and settling of calcite from sea water, or by precipitation from waters within newly deposited sediment. Micrite, fine crystalline settled material, is considered as matrix in a rock - the fine deposited material among the allochems. Sparite is calcite which precipitates within the sediment to form a cement, binding together the matrix and the larger fragments. Later recrystallization is able to destroy textures within both the matrix and the allochems and even to obscure distinction of the three components.

Limestones can be formed entirely of orthochems. Microcrystalline calcite may form by precipitation with or without coarser crystalline sparite filling the larger cavities. Limestone can also be made entirely of organic reefal organisms or of skeletal remnants.

Those limestones having non-calcareous transported material may be called argillaceous (shaly), silty, or sandy limestone. When silica precipitates from the water (sea water or connate pore water), the limestone becomes siliceous or cherty.

3.2.2 Massive Crystalline Limestone

Massive Limestone is well cemented and has a very low clay content. As a result, it is strong and resistant to weathering. Often it forms layers up to two and a half meters thick. Fossil content is typically very low in deep water limestone while limestone formed in shallow water where colonies of reef forming organisms lived, is largely organic.

Aphanitic Limestone is usually light tan in color, sometimes with a pink hue, and is very brittle. When broken, it shatters into shards that may show conchoidal fracturing. It is very hard, and by definition it is extremely fine grained. Its appearance in hand sample is of angular fragments in mutual contact or with only small amounts of light grey, slightly argillaceous matrix between.

Micrite is a fine-grained, grey limestone having a regular crystalline, isotropic texture. While Aphanitic Limestone has few recognizable fossils, Micrite has a low fossil content (up to 10%). Micrite having more than 10% fossil content is termed Biomicrite or Biolithite. Biolithite is the term used in this report for all classes of sparry or micritic, fossiliferous limestones. Fossils in Biolithite are generally recrystallized and often infilled with sparite. Coquina layers formed of pure fossil fragments are uncommon. They are formed of shells of brachiopods and oysters in bands about ten cm thick or less. Shells in coquina layers are well cemented but are generally not recrystallized. They form tough, weather-resistant layers.

3.2.3 Nodular Limestone

Nodular Limestone is a combination of crystalline calcite and argillaceous lime mud. Variations in the volume ratio of calcite to clay causes strength to range from strong to medium weak. Most of the Moberly Member, as encountered in outcrop and core, is Nodular Limestone. Where clay content is low, core is firm, continuous and unbroken. In outcrop, all Nodular Limestone weathers much more rapidly than Massive Limestone and produces rubble having low cohesion.

Nodular Limestone is the product of complex and not fully understood processes. The calcite is concentrated in fine-grained, ovaloid nodules that form most of the volume of the rock. The clay occurs in the fine-grained matrix which forms a fingering patchwork of softer, darker colored and poorly cemented lime mud. There is a layer around each nodule in which calcite grades outwards into the clay-rich matrix. Size is uniform, most nodules being from two to five cm in their long dimension. However shape, angularity, and arrangement are highly non-uniform. The process of deposition is visualized as occurring in deeper, quiet water where settling of fine calcite (produced by chemical or biologic activity) was continuous while deposition of clay that had been eroded and transported from land was periodic. This would have resulted in clay-rich and calcite-rich layers. Compaction and squeezing could have caused lensing of these layers. Subsequent processes of gentle to turbulent slumping (perhaps triggered by earthquakes) would result in fragmentation of partially cemented calcite lenses and the transport, partial rounding, and redeposition of the still plastic fragments. The uncemented clay-rich mud would have behaved as loose sediment and been redeposited as laminae or partially squeezed or resettled between the fragments. Although fossils are rare in this deeper water environment, some nodular layers contain shell fragments deposited during times of low clay deposition or occasional periods of shallower water, or transported with the calcite mud during slumping.

3.2.4 Shaly Limestone and Shale

Rock types of this group have a high clay content and a low rock-mass strength and the more clay-rich types also have very low intact rock strength. When cored, these rocks break apart easily and in outcrop they are recessive. They weather to either a soft plastic mass or to platy layers of hard limestone separated by soft clay-rich laminae or bands.

Shale encountered in the Waterways Formation is calcareous and greenish, having a darker color than the limestone. It is laminated and partly fissile. Calcareous Shale is dominantly shale but contains bands of low-clay limestone.

ShaLy limestone contains a higher proportion of calcite than does calcareous shale. It has thicker bands of more pure limestone separated by soft calcareous shale.

In outcrops, the banding effect may be accentuated by weathering. Both calcareous Shale and shaly Limestone can be termed 'banded limestone' for the purpose of core logging. Fossils occur in some of the thicker limestone bands (> 5 cm) and less commonly in shale bands.

Disseminated Argillaceous Micrite is a cohesive micritic limestone that formed in deep water by deposition of a mixture of clay minerals with precipitated calcite. Abundant sea floor organisms produced burrows which are preserved. This biologic activity, known as bioturbation, is likely the cause of the intimate dissemination of clay throughout the lime mud. Cores of this rock are strong.

3.2.5 Other Rock Types

Norris (1963) encountered sandstone and sandy limestone in outcrops of the Christina Member near the mouth of the Christina river. Quartz sand was observed by one of the authors filling enlarged fractures near the top (to 5 m depth) of a limestone core from the upper surface of the Waterways Formation (corehole Shell Eatha, 12-6-99-8W4, Christina Member). The sand-filled channelways encountered are about four cm wide and of unknown length. The fill material is quartz sand with some clay and is partially cemented with calcite. It is stained by, and contains bitumen.

Limestone sand formed of sand-sized particles of limestone, including fossil detritus, occurs infrequently and in minor amounts within some of the fossiliferous rocks.

Silicified and silty limestone and silicified limestone breccia were encountered in several core intersections.

3.3 Sedimentary Features

Sedimentary features in the Waterways Formation include fossils, lamination, and bedding separation planes. Their occurrence and characteristics are dependent on rock type. Nodules, previously discussed, are features restricted to Nodular Limestones.

3.3.1 Fossils

Fossils are not numerous in the argillaceous rocks (Nodular Limestone and Shaly rocks), but in Massive Limestone, fossils and fossil fragments are a major constituent. Brachiopods are the most prevalent type of fossil and can be found in most rock types and in all members of the Waterways Formation.

The Moberly Member has abundant brachiopods and in addition cephalopods, gastropods, pelecypods and stromatoporoids. Stromatoporoids are algal structures identified in outcrop and have been observed up to one metre in size.

3.3.2 Laminations

Lamination is best seen in argillaceous rocks which can be very finely to very coarsely laminated. Some common lamination features are shown in figure 14. Very finely laminated Shales are fissile and are readily broken apart into flakes. In banded limesone, there is interlamination of clay-rich and calcite-rich layers. These laminations are sometimes wavy or crenulated. The interlamination on a coarser scale results in argillaceous platy limestone. The bands of limestone have a gradation towards their centre from shale to calcite (figure 14). The upper and lower edges of the limestone become progressively softer and darker grey because of increasing clay content. The matrix in some Nodular Limestones is laminated in a wavy and irregular manner. Lamination in Massive Limestone occurs only in some of the fine detrital material and is poorly exhibited.

3.3.3 Bedding

The development of bedding in the three groups of Waterways Formation rocks is greatly variable. In Shaly Limestone, bedding is closely spaced and is exhibited as fissility or banding. Within Nodular Limestone layers, bedding is poorly developed and in core is definable only where there are laminations of clay that extend across the width of a core. Some Nodular layers have no internal bedding separation planes. In Massive Limestone layers, bedding separation planes occur regularly. Thin strata (less than about 0.7 m) may have no internal separation planes. Thicker layers usually have bedding planes spaced at from 25 to 60 cm (plate 4).

Bedding planes are accentuated by weathering in outcrop and are readily observable. Core breaks preferentially along bedding in most of the rock types but Massive Limestone often exhibits no preferred breaking direction.

3.4 Geometry of Bedding and Joints

3.4.1 Method of Study

Discontinuity features studied during logging of Waterways Formation core were:

a. spacing of core fractures as removed from core barrel and the type of fracture (eg. along bedding)

b. spacing of readily hand-breakable fractures

c. surface topography of fractures.

It should be noted that most fractures in core were aligned parallel or almost parallel to bedding whose direction was determined from lamination, lithology contacts, alignment of clasts or drilling abrasion features.

In outcrop, bedding is more obvious because bed separation and erosion along bedding planes are promoted by weathering. Weathering also removes some of the fine details of bedding planes. Only approximate values of bedding spacing were recorded from the examined outcrops.

Joints encountered in core were characterized according to lithology and surface features (profile irregularity, weathering and surface coating) and were subjected to direct shear tests (see section 4.3). Jointing in outcrop was studied by line survey in which a horizontal line was placed along the outcrop and the dip and dip direction of joints intersecting the line were measured. There are some practical limitations which can introduce biases in line surveys. For instance to speed data collection it is usual not to measure very short joints which have only limited engineering significance. In this study a lower limit of approximately 30 cm was placed on the trace length of joints. There can also be a directional bias resulting from the unvarying orientation of outcrops and from lack of nearby outcrops of differing orientations. Directional bias is the tendency of structures parallel or near parallel to the outcrop face to be poorly exposed and to be missed during a line survey. The outcrops surveyed for this study have irregular zig-zag faces, which reduces the directional bias. A bias towards underemphasis of joint sets having wide spacing (or wide apparent spacing, as do sets nearly parallel to the outcrop face) was reduced by making the line at each outcrop as long as possible. Because all joints of the Moberly Member were near vertical (as are joints in all other members, as far as is known), the line surveys were conducted horizontally along the outcrops near river level. Features noted for each joint intersecting the survey line included:

1) Location, dip and dip direction - measured by tape and Clar compass. For curving joints or fractures intersecting a flat outcrop face, approximations were necessary, both for orientation and surface features.
2) Rock unit in which joint occurred and extension into other units.
3) Length (vertical distance) and breadth (horizontal distance) - many joints were short as they were present only in one unit (generally of Massive Limestone). Many joints continued beyond the outcrop and neither full length nor full breadth were determined.
4) Planarity - an approximate measure on a large

scale (0.5 m or more) of joint surface flatness. For joint traces, this was reduced to a two-dimensional estimation. An assessment of joint surface irregularities was made by reference to the indices illustrated in figure 15.

5) i-angle - an approximate measure of the steepness of joint surface waviness, measured by a Clar compass over a length of approximately 10 to 20 cm (figure 15b).

6) Roughness - a measure of small irregularities on a joint surface, measured over a length of about two cm (figure 15c).

7) Infilling of joint or staining or alterations of joint surface.

Supplemental joint orientation data from two outcrops was provided by Dr. M. Dusseault, Department of Mineral Engineering, University of Alberta.

3.4.2 Lithologic Control of Structure

Lithology appears to have little relation to large scale structures such as faults or folds. However jointing in the Waterways Formation is related to lithology in the folowing ways:

a) joint occurrence, spacing and continuity

b) joint regularity in orientation and planarity, and regularity in existence as a single (rather than multiple) feature.

The significant effects of lithology on bedding are discussed in the following section (3.4.3) and the effect on jointing in section 3.4.4. Two characteristic patterns of jointing and fracturing are noted: one in strong lithologies and another in weak. Strong rocks are Massive Limestone and the strongest of the Nodular Limestones. Weak rocks include weak Nodular Limestones and Shaly rocks. For the purpose of bedding characterization, three groupings could be made: strong (Massive Limestone), Nodular and weak (Shaly rocks).

3.4.3 Bedding Characteristics

The spacing of bedding separation planes between lithologies is determined by the changing depositional environment.

Bedding within Massive Limestone at one outcrop is spaced from 25 to 60 cm and bedding planes are continuous, planar and moderately rough.

In Nodular Limestone, bedding results from deposition of argillaceous laminations. Bedding planes become more closely spaced when there is higher clay content; high-clay Nodular Limestones tend to have more clay laminations that are continuous. Spacing of bedding in Nodular Limestone varies from several cm to one meter. Bedding tends to be very rough.

In Shaly rocks, spacing of bedding separation planes varies from fractions of a mm (fissility) to several cm (banding). In Shales, the bedding is very planar and is very smooth or moderately rough (crenulated, as seen in some core).

Tensile strength across bedding separation planes in Nodular and Shaly rocks is very low and core pieces can therefore be easily fractured. A numerical assessment of the occurrence of easily hand-breakable fractures has been made of the corehole WW1 (figure 11).

3.4.4 Joint Occurrence

Jointing is accentuated by weathering in outcrop (plate 5). Two effects of weathering were noted. First, there is a general loosening of the outcrop (surficial creep and movement due to stress relief, erosion of softer layers and frost action). This causes joints to open and creates new fractures. The frequency of jointing in outcrop may therefore be greater than at depth. Second, outcropping joint surfaces are weathered by dissolution and erosion so that observed surface features may differ from those underground.

All joints examined in this study were rough, near vertical tension joints. Joint waviness and planarity are usually well correlated, so that highly non-planar joints are also wavy and often split into two or more fractures which diverge or follow bedding. Joints in the thinner, Massive beds are short (one metre or less), regular in orientation and planar. Short joints in weak and highly weathered beds tend to be very irregular. Longer joints in thick Massive beds are readily observable but often quite irregular. Figure 16 summarizes the joint characteristics for the three major lithologic groups (plate 6).

Most joints encountered in Massive layers did not enter the weak layers or penetrated only a short distance. The characteristic surface irregularity and low continuity of joints in the weak strata are largely due to the very close spacing of bedding or laminations (both of which can be non-planar). Figure 17 illustrates the regularity of jointing in strong strata as opposed to the irregularity in weak strata. Observation of jointing is difficult in weathered outcrops of weak strata.

3.4.5 Joint Orientations

Orientation is one of the most important joint features and is the basis for differentiation of sets. Joint surveys were conducted on four outcrops of Waterways Formation strata (see map, figure 6): at Mountain Rapids on the upper Athabasca River (Mountain Outcrop), at Moberly Rapids (Moberly Outcrop) one kilometre west of Fort McMurray, on the west bank of the Athabasca River near the north end of Stony Island (Stony Outcrop) and below Lookout Point on the Mackay River (Mackay Outcrop).

Four major joint sets have been delineated (figure 18). The joint sets form two orthogonal joint systems closely corresponding to those of Babcock (1975). Figures 19 a to d present stereonets, with interpreted joint sets, of joint data from each of the outcrops examined. Variations in lithology and local structure likely account for some of the differences of joint set orientation between widely separated outcrops. Frequency charts (figures 20 a to d) present the same joint dip-direction information but do not illustrate the differentiation of sets as well as the stereonets. Figure 21 charts features of all the joint sets.

At all of the outcrops, joints from three of the four sets were recorded, that is both sets of one system and a third set from the other system. However at each outcrop, at least 75% of the joints of the third set are recorded as "irregular fracture" or "trace, perpendicular to outcrop". There is no certainty that these features represent a joint set. They may be traces of joints of another set or they could be fractures formed in the outcrop by weathering. Thus it is concluded (as does Babcock, 1975) that only one joint system (with two sets) occurs at each outcrop. The joint surveys conducted for this report indicate that there are numerous random joints (at least in outcrop). The same joint set varies in dip-direction by as much as 14 degrees so that there is near overlap of sets when considering all the data together. Average dip of each joint set can be considered vertical with deviation of up to 17 degrees from the vertical in either direction (eg. standard deviation of dip of joint set 3 at Moberly Outcrop = 16.6 degrees). The orientations of many non-planar joints were imprecisely measured because of limited exposure or because of lack of a planar surface. Joint set strike orientations defined by this study and by previous studies are presented in figure 22.

3.4.6 Joint Spacing and Continuity

Joint spacing is highly variable from outcrop to outcrop and among the joint sets, and it also varies for any given joint set present in different lithologic units at the same outcrop. This latter effect is most clearly seen at the Mountain Outcrop where joints of two sets are very closely spaced (both about 0.65 m) in a thin unit (0.6m) of Massive Crystalline Limestone. In a thick unit of similar lithology, the spacing is several times wider. In platy Nodular units at Mountain Outcrop, the joints appear to be even more widely spaced.

Joint continuity for all sets is poor. Joints are most often limited to one strong (Massive) unit with poor expression in a weak, non-Massive unit immediately above or below. Continuity or length of joint was indexed at three outcrops according to the number of stratigraphic units in which it occurred (possibly non-continuously, as when a joint would occur in two units of Massive Limestone but not in the intervening Shaly unit). Values are conservative because erosion and cover at the top or base of most outcrops prevented full exposure of many joints. Lengths in metres measured at the MacKay Outcrop are typical (2-2.5m), but similarly conservative.

3.4.7 Joint Surface Topography

The irregularities on the surface of a joint are divisible into small, medium and large scale: roughness, waviness and planarity (section 3.4.1 and figure 15). Roughness and planarity were visually assessed on a scale from one to five (five is very rough, or very non-planar). A value for waviness was determined by measuring the steepness angle (i-angle) of a typical medium scale surface irregularity (a hollow or bump about 10 to 20 cm across).

Roughness indices, which are averaged for each set at each outcrop (figure 21), show very little variation. Most joints have an average roughness index of 3.0 (3 is moderately rough), although all sets exhibit a complete range of roughness. Many joints observed were fully exposed to weathering by surface waters which made the joint surface smoother. It is considered unlikely that dissolution by water has enhanced roughness of any surfaces. Roughness does not appear to correlate with other measured features. The Mountain and Stony outcrops provide conflicting evidence of a relationship between roughness of joint and thickness of jointed strata (figure 21).

Waviness tends to correlate with thickness of the jointed stratigraphic unit. Unit Two at the Mountain outcrop, which is only 0.61 metres thick, contains joints of sets II, (III) and IV, which are all much less wavy than those joints occurring in 2.1 m thick unit 4 and the same outcrop (figure 21). At the Stony outcrop where comparison was also possible, no relationship was found between waviness and thickness.

A planarity versus thickness of strata relation was examined only from data collected at the Stony outcrop. No relationship was observed. The very low planarity index (well planar) of all joint sets at the Moberly outcrop may be due to the small thickness (0.61 m) of the jointed strata examined, which prevents full expression of the feature of planarity.

Both planarity and waviness indices are higher in Nodular Limestone than in other lithologies. Jointing in Nodular Limestone is difficult to characterize because of weathering, but joints are noticeably more irregular than in Massive Limestone, and have less planarity and a higher waviness. Joints in Nodular Limestone also have a habit of splitting and terminating in multiple fractures having non-uniform orientations.

3.4.8 Joint Staining and Infilling

Infilling and staining of joints at outcrops may not be indicative of joints at depth. Joints at all outcrops are subject to solution and erosion effects from rain and surface waters. Two of the outcrops studied (Stony and MacKay) have probably suffered periodic flooding, and showed only two joints which were not washed clean of staining. At the Moberly outcrop a number of joints have rust-colored staining (figure 21). At the Mountain outcrop, a high percentage of all the joints were rusty colored, some were tarry, and many were covered by a rusty-colored layer of calcite about one mm thick or less.

Joints in core contain tar to a considerable depth below the Oil Sands (greater than 30 metres). It is believed that most joints at one time contained tar that had penetrated from the overlying McMurray Formation, but that upon exposure the bitumen was washed from the joints and fractures. Joints at the Mountain Outcrop therefore may be more similar to joints at depth than other outcrops, with respect to bitumen and also with respect to calcite infilling. Fourteen percent of the joints at Mountain Outcrop contain a calcite film; 7% in each set of joint system two. There was no evidence that the calcite acted to cement the joint blocks into a cohesive mass. Joints and fractures in another limestone outcrop of the Moberly Member which was not examined in detail were observed to contain tar.

3.4.9 Summary of Discontinuity Geometry

The study of geometry of discontinuities in Moberly Member outcrops reveals several features important in relation to stability of underground excavations. The number of joint sets at one location appears to be only two (orthogonal). However there are a large number of random fractures, some of which may be surface features caused by exposure. Although joint dips are detrimental, the orthogonal orientation of the joint sets is beneficial to stability of roofs of openings. All joints encountered in core were near vertical, as are those in outcrop. The random joints have steep dips and in addition appear to be oriented in all directions. Continuity of joints is poor. Most joints do not continue through more than two stratigraphic layers. Joint spacing is highly variable and in part is dependent on lithology and thickness of layer. Spacing ranges from 0.6 to 4 metres for each set in Massive and 1 to 4 metres for each set in Nodular Limestone. In thin layers of Massive Limestone, joints are regularly spaced and average spacing is approximately the same as thickness of the layer. Joints in thick layers are often unevenly spaced, but average spacing is again roughly the same as thickness. Joint surface topography is rough on the small, medium and large scale. Most joints are rough, wavy and non-planar. Waviness and lack of planarity are greater in joints in weaker strata. In Shaly layers and some weak Nodular layers, joints are very wavy and highly non-planar.

Bedding is greatly controlled by lithology. It is generally closely spaced (1 cm), smooth and weak in banded limestone and widely spaced (0.5 m) and rough in Nodular and Massive Limestone.

4. PROJECT DATA - STRENGTH OF STRUCTURAL DISCONTINUITIES

Mechanical behavior of the Waterways Formation in underground excavations will be primarily determined by the orientation, continuity, spacing and mechanical properties of planes of weakness, by the mechanical properties of the intact rock, by the orientation and magnitude of the virgin stresses and by the shapes and distribution of excavations and their method of excavation.

Chapter 3 has described the geometry of planes of weakness while in this chapter their strength and mechanical properties are discussed. Mechanical properties of the intact rock are treated in chapter 5. Chapter 8 discusses in-situ stress and methods of excavation and is then able to summarize rock mass strength and to indicate the mechanical behavior around underground openings in the Waterways Formation.

4.1 Method of Strength Determination

Structural discontinuities in the Waterways Formation include bedding, which generally is near horizontal throughout the region, and jointing, which is approximately perpendicular to bedding. Joints and bedding reduce rock mass strength. Shear strength of joints and bedding in Waterways Formation rocks was studied by means of laboratory direct shear testing of joints and bedding planes sampled from core and by field evaluation of outcropping joints.

Shear strength is in part dependent on physical features of the surface of the discontinuity, and a preliminary assessment of the shear strength of large joint surfaces in the field can be made by comparison with the strength and physical features of specimens tested in the laboratory.

4.2 Shear Testing - Method

Direct shear tests were performed on a Leonard Farrance Direct Shear machine (plate 7). Maximum practical specimen size is about 80 x 80 mm. Shearing can be performed in only one direction for a distance of 9.5 mm. During testing, shear resistance was measured by means of a calibrated proving ring and vertical and horizontal displacements were measured by separate dial gauges. Normal stresses were essentially constant during each test (computations of stress included area corrections to account for shear movement). Each specimen was tested several times at increased normal loads. This required specimen repositioning after each test to the original position of zero horizontal displacement.

During shearing of irregular surfaces under constant normal stress, shear resistance increases to a maximum (peak strength) and then drops as shearing continues (figure 23a). Residual strength is the minimum post-peak shearing resistance at the specific level of normal stress. For an irregular surface in brittle rock, shear strength increases with increasing normal stress (figure 23b). As asperities on the rough surface are sheared off, normal stress has less of a beneficial impact on shear strength. When all small asperities are sheared off, the relation between normal stress and shear strength is expressed as the residual angle of effective shearing resistance.

4.3 Joint Shear Tests - Results and Discussion

Laboratory direct shear tests were performed on seven separate joint specimens obtained from core drilled in core hole WW1. Figure 24 tabulates test conditions and results for joint shear tests. Figures 25 a to g show the graphical relation of shear strength to normal stress for each joint test. Shear test results on bedding are tabulated in figure 26.

4.3.1 Effect of Moisture, Clay and Weathering

The joint shear tests were performed from six to nine months after coring of hole WW1. All specimens were stored in a moisture chamber with near 100% relative humidity, and moisture content of the core is assumed to have changed little over this period. Submergence before and during testing (from 11 to 40 hours) ensured that each specimen was virtually water saturated, so that results reflect saturated ground conditions. The presence of water during shearing softened intact rock asperities and promoted their breakage at stress lower than when dry. Broken and sheared particles, especially those with clay, have reduced shear strength when water softened. Limestone which is weathered or which contains clay minerals is softer and weaker than unweathered crystalline limestone. It is not possible to directly correlate rock softness with determined angles of shearing resistance because of other factors (i.e. joint roughness, mineralogy, and imprecise assessment of rock softness and of joint roughness).

4.3.2 Bitumen Infilling

All joint surfaces encountered in core were coated with bitumen, which also impregnated the rock for from one to five mm. Highly oxidized bitumen imparts a brownish stain to the impregnated surfaces. Slightly oxidized bitumen which forms a film or a thin lense on the joint surface is black, although partially hardened and less sticky than bitumen in rich Oil Sands. Very weak apparent cohesion across two joints was likely a result of sticky bitumen.

In test specimen #40b, the joint surfaces retained their coating of bitumen even after many separate shear tests. Bitumen may have four effects on shearing of joints. Two beneficial effects are protective cushioning of asperities during shearing and long term protection of the joint surface from weathering. Two deleterious effects appear possible: that bitumen acts as a lubricant and that it reduces total effective normal stress.

4.3.3 Joint Roughness Profile

A profile of each joint surface was used to estimate Joint Roughness index (figure 27). The Joint Roughness index is a numerical assessment of surface roughness ranging from one for smooth surfaces to five for extremely rough surfaces. All specimens were moderately rough with large asperities which provided a high degree of interlocking. At low effective normal stress these rough asperities provided high shear resistance and therefore produced high peak angles (ϕ_{pk}) of effective shearing resistance. As effective normal stresses increased, asperities were crushed and sheared, the amount of interlocking was reduced, and the angle of effective shearing resistance lowered to the residual angle, ϕ_r .

There is poor correlation between the roughness profiles and the measured angles of effective shearing resistance (figure 24). Any relation of sharpness and size of asperities to peak friction angle of a joint specimen is difficult to confirm because measured peak angles are all similar (61° - 75°). Variations in peak friction angles may be due to differences of asperity size as well as differences in lithology or extent of weathering. Friction angles recorded as final have a wider range (25° - 49°). The two specimens with high final angles (#8b of 44, and #40b of 49) had large asperities. It is possible that for these two specimens the normal stresses applied during testing were insufficient to attain their residual angles. In these two cases, shear motion would be at an angle "i" to the horizontal and the final angle of shearing resistance measured would be greater than residual by the amount "i".

An unexpected increase of final angle resulted when specimen #9/10-2 was retested at low stress levels following standard determination of peak and final angles at higher normal stresses. This phenomenon is anomalous and no explanation is offered.

4.3.4 Joint Shear Strength in Relation to Mining Conditions

Initial peak angles of effective shearing resistance determined by testing are high and may be attributed to the joint surfaces which are moderately rough to very rough, as seen both in core and in outcrop. Also, joints in outcrop are wavy and non-planar (section 3.4.7).

In some of the joint tests detailed in section 4.3.3, the final angles are reduced by the presence of clay minerals or weathering products (specimens #4b, #41a). However, use of final angles determined in the laboratory is conservative because joints in the Waterways Formation have not been observed to have undergone shear displacement. They would have less disintegration of the rock along the joint surface than that attained during the series of test shearings and therefore the amount of shearing resistance initially mobilized under conditions of stress imbalance would be much more than that calculated using final angles.

The component of frictional resistance in resisting sliding of blocks in the jointed roof of an excavation will be small unless horizontal stresses are significant. In particular situations where joints dip away from each other, friction will play no part. The possibility that the calcite infilling of some joints at Mountain Outcrop (section 3.4.8) is widespread at depth and that it cements blocks together, is highly important. Even partial cementing along joints would greatly increase rock-mass stability and reduce joint-induced failures.

4.4 Direct Shear Strength Along Bedding

Direct shear strengths of bedding discontinuities were also determined in the laboratory (refer to figure 26). Specimens from core were stored in a high-humidity chamber until testing. Bedding plane characteristics for the main rock types are described in section 3.6.3. Bedding in rocks with low clay content is rough and irregular (similar to joints in the same rock). Some low-clay Nodular Limestones can have clay minerals concentrated along bedding planes. In a similar way the clay-rich rocks also have clayey bedding planes, and these rocks can be grouped together on the basis of their low effective angles of shearing resistance along bedding. Those bedding planes which are clay-free were not tested and it is assumed their behavior is similar to behavior of rough joints as discussed in section 4.3.

Three clay-rich bedding planes were laboratory tested in direct shear (figure 28 and 29). Initial peak angles of effective shearing resistance when dry (54° - 65°) are only slightly lower than those for submerged rough joints in hard limestone. The dry final angles of 32° to 52° are also somewhat below final value for submerged joints. Final angles for submerged bedding planes were only slightly reduced from the final angles of dry bedding planes, which suggests that the soft clayey material does not contain expanding clays.

5. PROJECT DATA - PHYSICAL PROPERTIES OF THE INTACT ROCK

5.1 Engineering Measurement of Lithologic Effects.

Geotechnical characteristics of the Waterways Formation are largely determined by lithology. A description of lithology such as in section 3.2 provides much data concerning the likely magnitudes of intact rock strength and shear strength properties of the planes of weakness. A rapid geotechnical assessment at any location in the formation based on lithologic information will be possible when the general relationship between lithology and rock properties is established. Section 5.4 summarizes the relationship for the Waterways Formation.

The following rock properties were measured by tests performed on samples of intact rock obtained from outcrop and core:

1. Fundamental Physical Properties and Composition
    a. Mineralogy - Carbonate Dissolution
    b. Specific Gravity
2. Intact Strength
    a. Uniaxial Compressive Strength
    b. Uniaxial Tensile Strength
        1) Direct Pull Test
        2) Brazilian Test
        3) Four Point Bending Test
    c. Triaxial Compressive Strength
    d. Cohesion - Double Shear Test

3. Rock Deformability
    a. Elastic Constants and Creep Characteristics
4. Intact Strength - Index Tests
    a. Porosity
    b. Ultra-Sonic Velocity
    c. Point Load Test
    d. Impact Toughness Test
    e. Hardness Tests
5. Effect of Water
    a. Slake Durability Test
    b. Swelling Test

A number of these tests measure innate rock properties while the remainder provide indices relatable to rock mechanical behavior. The intact rock properties, presented in this chapter, further enhance the delineation of lithologic types.

Figure 12 classifies the Waterways Formation into eleven rock types. Figure 30 summarizes results of this chapter in chart form to characterize the most common rock types according to their intact geotechnical properties.

5.2 Laboratory Tests Conducted

5.2.1 Composition

Mineralogical composition is a guide to other rock properties. In the Waterways Formation, carbonate and clay minerals form from 95% to 100% of the total mineral content. The quantity of clay affects all of the intact rock properties as well as influencing properties of rock discontinuities (sections 4.3 and 4.4). The type of clay mineral can also be very important. Hard minerals such as quartz influence the performance of drills and tunneling machines. Common sulfide minerals can accelerate the weathering of dimension stone, the deterioration of cement or can prevent use of the limestone for air pollution control processes.

Clay content was determined by the carbonate dissolution method, which measures clay content as a weight percent of the total rock sample. Calcite, dolomite and halite react with hydrochloric acid and form soluble products while clay, quartz and sulfide minerals are nonreactive and remain as residue. For this report, percentage clay is considered equivalent to the percentage residue. Samples, of less than 100 grams, were prepared by crushing, grinding, sieving (-60 mesh) and drying. Dilute hydrochloric acid (15% HCl) was added until there was no further reaction. The solution was left a further 24 hours to ensure complete reaction, then was washed, filtered, dried and weighed.

5.2.2 Specific Gravity

Specific gravity is a measure of the amount of mass per unit volume. Dry specific gravity is controlled by mineralogy and porosity, and therefore can be used as a method of assessing variations in these two properties. Dry specific gravity was determined by measurement of weight and volume of regular cylindrical specimens. Volume was calculated from caliper measurements of specimen diameter and length. Dry weight was measured as follows:

- either air dry (dried at room temperature and humidity for at least one week) or,
- oven dry (dried at 120 degrees C. for at least eight hours).

Air dry and oven dry specific gravities were determined to differ by less than 0.10%.

5.2.3 The Uniaxial Compression Test

The uniaxial compressive strength of geometrically regular laboratory specimens has been related to the strength of large masses of rock and to the support capability of mine pillars. The extrapolation of strength from laboratory to field scale has many qualifications but is possible because of many years of accumulated research and practical experience. Some difficulties of extrapolation result from variable test procedure (no internationally accepted standards), inhomogeneity of rock, and qualitative differences between intact rock and rock masses. Thus, for rock engineering design, uniaxial compressive strength must be combined with other information and with experience before prediction of rock mass strength can be made.

Specimens tested in uniaxial compression were prepared and tested according to the specifications of the

International Society for Rock Mechanics (ISRM). Testing was performed in an MTS servo-controlled compression frame having a digital and graphical read-out. The compression frame is capable of applying a load of 27.6 KN. Specimens, all cored perpendicular to bedding, were right cylinders having a length to diameter ratio of approximately two. Loading rates during testing, for both saturated and dry specimens, were either 0.102 or 0.203 mm per minute.

5.2.4 Tensile Strength - The Direct Pull Test

The strength of rock under uniaxial tension is important in the investigation of stability of roofs of underground openings. A rock mass broken by continuous joints has no tensile strength, but a rock mass with non-continuous joints has tensile strength across 'rock bridges'. Tensile strength determined by laboratory tests on specimens of intact rock can be extrapolated to the rock mass tensile strength if joint continuity can be evaluated.

Uniaxial tensile strength was determined by direct-pull tests performed on right-cylindrical rock specimens prepared to the same specifications as for the uniaxial compression test (plate 8). The specimens were failed by tensile loading in an Instron Testing machine using cables and metal platens attached to the specimens with epoxy. Figure 31 shows the test set-up for the Direct Pull tension test. Uniaxial

$$\text{tensile strength,} \quad t = \frac{P}{A}$$

where: P = tensile load at failure

and : A = cross sectional area of specimen perpendicular to core axis.

The major experimental difficulty with this test is ensuring regularity of specimen geometry so that misalignment of applied forces during loading does not induce bending forces which initiate premature failure.

5.2.5 Tensile Strength - The Four Point Bending Test

Tensile strengths determined by bending tests have been used in estimating roof spans of underground openings. Tensile strength is determined from bending tests by using elastic beam theory to calculate the stresses at the point of failure in a bending beam.

Four point loading using the Instron testing machine was performed on right cylindrical specimens (figure 32 and plate 9). The maximum tensile stress which fails the specimen occurs along the lower surface of the specimen between the two upper steel rods through which stress is applied.

$$\text{Tensile strength, } \sigma_t = \frac{2P_{max}(l-a)}{\pi r^3}$$

Pmax = maximum applied load

r = specimen radius

l = length of unsupported beam

a = distance between loading points.

It is very important to align the loading and supporting rods so that the loading geometry is symmetrical. Bending tests may be performed on specimens cored at any desired angle to bedding. Tensile strength from the Bending test has been found to be about twice as large as the tensile strength determined from the direct-pull test.

5.2.6 Tensile Strength - The Brazilian Test

The Brazilian test is another indirect method of determining tensile strength. Preparation and testing procedure are simple and not time consuming and results are more consistent than for other tensile tests. Rock which is too weak to prepare for other tests can be tested by this method. The Brazilian test has been used to study anisotropy in rock.

Rock discs, with thicknesses from 0.35 to 0.80 times the diameter, were compressed across a diameter in a Wykeham Farrance stepless compression machine until tensile failure occurred (plate 10). Elastic theory allows the principal stresses to be calculated - compressive along and tensile perpendicular to the loaded diameter (figure 33).

$$\text{Tensile strength, } t = \frac{2P_{max}}{\pi D t}$$

where t = specimen thickness

Pmax = maximum load applied

and D = specimen diameter.

5.2.7 The Triaxial Compression Test

Triaxial compression tests provide values of compressive strength and deformability over a wide range of confining pressure. These results, together with uniaxial tension and compression test results, help to define the Mohr Envelope (the relationship between shear and normal stress acting on the plane of failure at the moment of failure of a specimen). Triaxial compressive strengths provide an upper boundary to the strength of rock underground under conditions in which it is confined in all directions.

The procedure for triaxial testing is similar to uniaxial compressive testing but the cylindrical specimen in addition is encased in an adiprene plastic sleeve inside a triaxial cell which allows axial loading while confining pressure is applied hydraulically to the curved surface of the specimen. The Hoek-Franklin triaxial cell was used with the MTS compression machine and no pore pressure measurements were made (plate 11).

Specimen preparation is identical to that for uniaxial compressive testing.

5.2.8 The Double Shear Test

The Double Shear test measures the cohesive component of rock strength resulting from cementation or other causes. A cylindrical core specimen is loaded uniformly perpendicular to the core axis along the mid-part of its length (figure 34). It is assumed to fail in shear perpendicular to the axis, with no normal stresses acting across the failure planes, so that:

$$\text{Cohesion, } c = \frac{P}{2\pi r^2}$$

where P = load applied

and r = specimen radius.

Regular cylindrical specimens were tested. Specimens were long enough so that the ends were at least one specimen radius from the nearest failure plane. Care was taken to minimize the generation of either bending stress or normal stress across the failure planes, by ensuring that the specimens were neither too loosely nor too tightly held in the apparatus.

5.2.9 Rock Deformability

The Modulus of Deformation (E) and Poisson's Ratio (ν) can be used to predict magnitudes of deformation of rock subjected to stress. Static values of both moduli can be determined by precise measurement of axial and lateral deformation and of applied stresses during axial compressive loading of rock specimens.

Because rock is imperfectly elastic, both the Modulus of Deformation and Poisson's Ratio are dependent on stress level and loading history and therefore have an infinite number of values. Modulus values and Poisson's Ratio determined in this study are tangent values from the first test loading, taken at 50% ultimate load (or during inital loading for two specimens which did not yield complete test results).

Specimens were prepared as for Uniaxial Compressive testing. Axial and lateral strains were measured by electrical resistance strain gauges attached vertically and circumferentially to the specimen by epoxy. Testing was performed with the MTS compression machine which recorded magnitudes of applied compressive stress. Axial and lateral strains were measured by using two Wheatstone bridges to average separately the values of strain indicated by the two pairs of strain gauges. Each pair was mounted on opposite sides of the specimen to compensate for differential strain across the specimen diameter.

Four similarly prepared cylindrical specimens of Aphanitic Limestone were creep tested in a hydraulic creep frame. Axial stress was increased to approximately 80% of ultimate strength. The intention was to maintain load at this level and observe long-term axial strain. Deformation was measured by dial gauge on the platens.

5.2.10 Porosity

Porosity is a measure of the void space in a rock. Absolute porosity (n) includes all pore space:

$$n = \frac{\text{volume of the voids}}{\text{volume of specimen.}}$$

Relative porosity measures the pore space of only those pores which are macroscopic and interconnected with other pores and with the specimen surface. Relative porosity can be determined by measuring the amount of water absorbed by a rock specimen in a specified time, for example one hour as in the Quick Water Absorbtion Index (Iv). The Quick Water Absorbtion Test immerses a specimen for one hour in a water-filled container under a vacuum of 10^6 tor (800 Pa). The specimen weights before the test when oven dry, and after one hour of submersion , are recorded.

$$I_v = \frac{\text{weight of absorbed water}}{\text{weight of dry specimen.}}$$

Relative porosities, of different rocks should be compared between specimens of similar size because of the influence, on Iv of the percentage of voids that is near the specimen surface and easily water-filled in one hour. Iv does not consider permeability, the rate of water penetration into the pores of the rock. The effect of differing specimen size and permeability on water absorbtion values was not investigated.

5.2.11 Ultra-Sonic P-Wave Velocity

The velocity of ultra-sonic compressional waves (p-waves) is an index of the strength and deformability properties of the rock. The velocity is dependent on mineral composition, density, moisture content, porosity, state of stress, and presence of fissures and fractures. All six of these features also influence strength. Laboratory measurements of ultra-sonic velocity can be used to assess the state of fissuring of intact specimens. Field measurements of velocity using accoustic logging in an AX drill hole have been correlated with the amount of pillar fracturing and with RQD (King, 1976). Blake was able to successfully determine pillar stresses before and after a destressing program, by using seismic velocities to determine state of fracturing (1972). The degree of fissuring and the mineralogy are two features of the Waterways Formation rocks which are much more variable than the other determinants of velocity, and therefore should be correlatable with velocity.

A Pundit ultra-sonic velocity measuring instrument was used. Electrically generated ultra-sonic pulses are transmitted by a transducer in contact (using a special silicone grease) with one end of right-cylindrical specimens, and are received at the other end by an electronic receiver. Specimen ends are ground parallel. Frequency of the ultra-sonic pulses is 54 hertz. Time of travel between the transducer and receiver is measured and recorded by the instrument while specimen length is measured by caliper. Test time per specimen with the Pundit is rapid; travel time can be measured more rapidly than the caliper measurement of specimen length.

5.2.12 The Impact Toughness Test

The resistance of rock to dynamic forces is measured by the Impact Toughness index test, which measures the ability of a specimen to absorb strain energy before failure. Impact toughness strength can be used to determine percussive drillability of a rock and its resistance to blasting.

The model CT-389 Rock Toughness Tester employed consists of a hammer of standard weight (2 kg) which is dropped onto the specimen from a height of one cm. Further impacts, from heights increasing each time by one cm, are imparted until the specimen fails. The Toughness Index is equal to the height in cm of the failing blow. Specimens were cylinders 25 mm in diameter and 25 mm in length, with ends ground plane and parallel.

5.2.13 The Point Load Test

The Point Load Test provides an index of rock strength which has been correlated with uniaxial compressive strength. It can be used as a simple, rapid and inexpensive means of rock testing.

Testing can be performed on regular or irregular specimens either in the field or in the laboratory. Specimen preparation for testing core or rough lumps is unnecessary. Testing procedure requires that the specimen dimension in the direction of loading be the smallest dimension.

The Point Load Tester applies load to opposite sides of the specimen through two co-axial conical steel platens of a specified geometry and hardness (figure 35). Tensile stress produced by this loading causes failure.

The Point Load Index, $Is = \frac{P}{D^2}$

where P = load at failure

and d = distance between platen points.

A Point Load Index, Tdp5, can be obtained from irregularly shaped field samples by testing 30 to 40 separate rock lumps in accordance with the statistical procedure proposed by N. Brook (1977, plate 12). Brook related the failure load to the fracture area (imprecisely measured) to enable the determination of the load needed to fail an equivalent specimen of five square cm area. This method of obtaining a point load index permits testing of field samples of weak rocks that may not be strength testable by any other method.

The Double Point Load Index Strength, Tdp5 (MPa) = $\frac{P}{5 \times 100}$,

The Point Load Index, Tdp5, is taken to be equivalent to the more familiar Point Load Strength Index, Is, of Broch and Franklin.

5.2.14 Hardness

Hardness is generally understood to be a measure of the resistance of a material to crushing by point contact. Measurements of specimen hardness are highly variable, reflecting variable test conditions and rock inhomogeneity. The hardnesses of Waterways Formation rocks were measured by two tests: the Vickers Hardness test and the Scratch Hardness test. Scratch hardness was measured during geotechnical logging of all core and outcrop samples. Vickers hardness was measured on four specimens in an attempt to correlate Scratch hardness with the more precise and well known (and also more time consuming) Vickers measure of hardness.

The Scratch Hardness test used a knife point dragged over a relatively large surface area of the specimen. Thus rock inhomogeneity was of lesser importance than the uncontrollable test conditions which include variation of applied pressure, of shape and area of point contact and of length of scratch. The test provides a subjective estimation of ease of scratching (measured on a scale from one, very hard, to five, very soft). Scratch hardness enables a rough assessment of clay content or degree of weathering, and reveals the presence of quartz.

The Vickers Hardness test uses a carefully specified test procedure. A small diamond point is indented onto a ground and polished surface with regular force. The point of contact is so small that inhomogeneity in crystal size, pore space, or rock cement can produce variable measurements. This variability necessitates measurements from a large number of individual tests to study the range of values and to obtain a representative measure of hardness.

5.2.15 The Slake Durability Test

Slaking, the breakdown of rocks by alternate wetting and drying, may occur in rocks containing clay. In mine openings, variations of groundwater flow, of air circulation or of the humidity of mine air can change the moisture content of exposed rock, and promote slaking and gradual sluffing of wall rock or cause roof falls.

The resistance of rocks to slaking can be evaluated by the Slake Durability Index Test of Franklin. In this test each specimen, consising of about ten roughly spherical lumps of rock weighing approximately 50 grams each, is submitted to two ten minute cycles of submerged tumbling in wire mesh baskets and oven drying. The weight loss resulting from the slaking breakdown of the specimen is recorded after each cycle. The Slake Durability Index (following the second cycle) is calculated as follows:

$$I = \frac{A - C}{A} \times 100\%$$

where C = dry weight of retained material
and A = dry weight of initial specimen.

5.2.16 Swelling Tests

Rock swelling results from the expansion of some minerals as they absorb or chemically bond water into their crystal structure. Bentonite and montmorillonite are examples of clay minerals that can expand to many times their thickness. In addition to mineralogy, the swelling ability of a rock depends on permeability, cementation, fabric and confining pressures. A swelling rock, if restrained from swelling, may exert large pressures.

Unrestrained swelling in underground mine openings aids in rock breakdown and failure. Swelling pressure magnitudes must be known to enable choice of restraining support. Rock swelling characteristics in underground mining may therefore dictate groundwater control techniques, support methods, amount of maintenance of openings, and equipment restrictions.

There are several laboratory tests by which the swelling characteristics of rock may be investigated. Two test methods employed in this study were the Free Swelling Test and the Confined Swelling Test. These swelling tests may be performed in any orientation with respect to bedding. The tests for this study measured axial expansion of specimens cored perpendicular to bedding (because of the presumed horizontal alignment of clay minerals, major swelling in a horizontal direction was not anticipated).

In the Free Swelling test, cylindrical cored specimens with ground and imprecisely parallel ends are submerged in water and allowed to swell freely. The amount of axial strain with time is recorded by dial gauge until there is no further expansion or until the specimen begins to disintegrate.

The Confined Swelling test uses specimens prepared similarly to those of the Free Swelling test. The specimens are restrained so that there is zero axial strain (measured by dial gauge). The test set-up provided no restraint to lateral expansion of the specimen. Zero axial strain was maintained by a Wykeham Farrance compression frame with a calibrated proving ring applying restraining pressure. The pressures exerted by the restrained specimen were recorded with time until pressure returned to near zero, due to specimen creep.

5.3 Test Results and Discussion

Test results presented in this section illustrate the different rock mechanics characteristics of the lithologic types. Reference to figure 30 facilitates correlation of tests within each lithology type.

5.3.1 Rock Composition

The results of the Carbonate Dissolution tests are given in figure 30. Measured amounts of clay in Waterways Formation rocks generally substantiate visual estimates.

Biolithic and Aphanitic Limestone appear in hand samples to be almost pure calcite, and by measurement they contain respectively 2.3% and 4.1% clay.

Nodular Limestone visually classified as 'low-clay', was measured to contain 18.3% clay. Two individual measurements were made of one sample of high-clay Nodular Limestone: one of the nodules and one of the matrix. The nodules contain 33% clay and the matrix contains 62% clay. The inability to separate nodules and matrix perfectly, caused inaccuracy in the measured individual clay contents (estimated at less than 5%): true clay content would be lower in the nodules and higher in the matrix. The tested sample of high-clay Nodular Limestone is about one third matrix, therefore the overall clay content (by weighted average) is 43%.

Two Carbonate Dissolution tests carried out on a banded limestone sample measured 61% clay in a shale band and 44%

clay in a limestone band. Gradation from clay-rich to limestone-rich bands introduces difficulty of precise measurement. Overall clay content of a typical banded limestone is therefore estimated as 53%. The measured value of 61% clay in the shale band is viewed as being representative of clay content in other calcareous shales of the Waterways Formation.

Hand-lens observation of core reveals that small amounts (1% - 3%) of disseminated iron sulfide minerals are common, especially in Nodular Limestone. Quartz was not detected in an x-ray analysis of clay-rich samples. Some silicified limestone was encountered in two separate core-holes. Silica is a minor constituent of most Waterways Formation rocks; very fine quartz grains, constituting less than 0.1% volume, were noted in several thin sections taken from core hole WW1 (see Appendix B for thin section descriptions). One analysis of Nodular Limestone performed by Steinkohlenbergbauverein in Essen, Germany indicated the following mineral content:

Carbonate and clay 98%

Quartz 1%

Opaques .... <1%

No heavy minerals and no feldspars were found.

5.3.2 Specific Gravity and Porosity

Specific gravity and porosity are strongly influenced by the amount of clay and cement.

All Biolithic rocks have almost identical and extremely low clay contents, but do have variations in the extent of their cementation. Two groups of Biolithic rocks are distinguishable on the basis of density and porosity. The less well-cemented Biolithic rocks are more porous (Iv = 1.33%) and are less dense (S.G. = 2.53). The well-cemented group has low porosity and higher density (Iv = 0.46%, S.G. = 2.64). There are some specimens that are intermediate in porosity and density. Water Absorbtion (Iv) appears to be independent of size in the Biolithic specimens.

Aphanitic Limestones are divisible into sparry, crystalline limestone and breccia-appearing limestone with a slightly argillaceous matrix. The sparry Aphanitic specimens have low porosity (Iv = 0.75%) and high specific gravity (S.G. = 2.63). Those Aphanitic specimens with minor clayey matrix have a higher porosity and lower density (saturated water content = 2.71%, S.G. = 2.52).

Nodular Limestones vary in their clay content from about 15% to 45%. Porosity, as indicated by Quick Water Absorbtion or by saturated water content values is low (Iv = 0.77%, saturated water content = 1.08%). Specific gravity is 2.56 and moderately variable (standard deviation = 0.031 grams/cc).

Specific gravity and porosity were not measured for most Shale or Shaly Limestones due to the extreme difficulty in preparing regularly shaped specimens and because of their tendency to break down in water. Measurements were possible on Disseminated Argillaceous Micrite and showed a moderate porosity (Iv =1.1%) and low specific gravity (S.G. = 2.53).

5.3.3 Ultra-Sonic P-Wave Velocity

Velocity measurements of ultra-sonic P-waves are distinctive for the major lithologies (see figure 30). Argillaceous limestones have low velocities compared to the crystalline Biolithic and Aphanitic Limestones.

Velocity measurements in Biolithic Limestone specimens vary from 3,400 to 5,600 metres per second. The average velocity is 4,730 metres per second (standard deviation = 670 metres per second) which reflects the well cemented and pure calcite nature.

A measurement of 5,340 metres per second on one specimen of Aphanitic Limestone indicates high ultra-sonic velocities in this well cemented, low-clay limestone.

Nodular Limestone specimens have an average velocity of 3,500 metres per second, despite having a higher clay content and containing more small fractures than Disseminated Micrite.

The low velocities recorded for Disseminated Micrite specimens (2,970 meters per second average, standard deviation of 310 metres per second) are attributed to the clay minerals which are distributed throughout the specimens. A possible explanation of the higher Nodular velocities may be that the close contact of the crystalline calcite nodules provides a nearly continuous, high-velocity travel path for the ultra-sonic waves.

The wide variability of velocities recorded, for instance in the uniform appearing Biolithic Limestones, may be due to undetected differences in cementation or bedding, or to inaccuracy in measurement techniques. To minimize interference with the sides of specimens of only 54 mm diameter, the wavelength of the signal should be made shorter by using a pulse frequency greater than 54 hertz.

Graphs of ultra-sonic velocity versus specimen density and specimen quality are presented in figures 36a and 36b. Before specimens were velocity tested, they were visually assessed and assigned a quality number, Qx. Qx is a combined measure of the clay content and the number of minor fractures, laminations or lithological contacts. Separate curves, drawn for each range of sample length, all reveal the same relationship of greater velocity in high density specimens and in specimens with good quality (low Qx and low clay). The different velocity relationships exhibited by the different sample lengths may be due to natural variation amongst specimens or they could reflect the greater inaccuracy of velocity measurements for the shorter specimens.

5.3.4 Hardness

Scratch Hardness values are presented in most of the lithologic core-hole logs. Figure 11 includes a scratch hardness log for core-hole WW1: Crystalline Biolithic

Limestone is moderately hard and Aphanitic Limestone is very hard. Disseminated Argillaceous and Shaly Limestones are soft to hard, while Shales are very soft. Nodular Limestones contain hard or very hard nodules in a matrix which, depending on clay content, is soft to very soft. Scratch hardness can be measured rapidly and easily and is a moderately accurate indication of intact strength of most rocks in the Waterways Formation because of the very close correlation of strength with lack of clay. Comparison of scratch hardness with rock-mass strength in figure 11 shows the correlation of values of hardness with the high Biolithic and Aphanitic Limestone strengths, the low strengths of Shales and the moderate strength of Disseminated Micrite. Low-clay and high-clay Nodular Limestones are distinguishable by the scratch hardness test.

Four Vickers hardness tests were performed, two on specimens of well cemented Biolithic Limestone and two on Disseminated Argillaceous Micrite (figure 37). Each test consisted of from eight to eighteen separate indentation measurements. The two limestone types are readily distinguishable. Biolithic Limestone has an average Vickers hardness of 144 and Disseminated Micrite of 108. Figure 38 shows that Vickers and Scratch hardnesses are correlatable and therefore that Scratch hardness testing by itself is a satisfactory measure of hardness.

5.3.5 Uniaxial Compressive Strength

Results of uniaxial compressive strength testing on five lithologies reveal that there is a general decrease in strength resulting from higher clay content. Based on visual observations, the absence of cement is directly related to the presence of clay.

Massive Crystalline Limestones have very little clay, are very well cemented with sparite and have high uniaxial compressive strengths (please refer to figure 30).

Nodular Limestones have moderate to high clay contents in the matrix and have uniaxial compressive strengths ranging from moderately weak to strong. Increased cementation and higher strength is noticeable in low-clay Nodular Limestone.

Disseminated Argillaceous limestones have a uniformly distributed clay content which restricts the extent of cementation and results in strong to moderately strong uniaxial compressive strengths.

Other Shaly Limestones, Shale and banded limestone core samples and outcrop samples were all too weak to withstand specimen preparation for the uniaxial compressive test. Uniaxial strength can be estimated from point load tests (see section 5.3.10 and figure 30).

Natural rock-variation amongst specimens results in large variances in measured values of uniaxial compressive strength within individual groups of 'uniform' specimens (i.e. coefficient of variation [illegible] 39% in the group of 41 mm diameter, saturated Biolithic specimens). The large variation prevents conclusive statements concerning effect of water saturation on compressive strength. Comparison between dry and saturated specimens of 54 mm diameter Biolithic Limestone from different locations must in addition consider differences in cementation, which affects strength. The saturated group is assumed to be stronger because it is better cemented. Differences of density and porosity (see section 5.3.2) do indicate that the saturated samples are extremely well cemented Biolithic Limestone while the dry specimens are less well cemented.

Also obscured by lithologic inhomogeneity amongst specimens is a possible relation of strength to specimen size. In Aphanitic Limestone (32 mm versus 41 mm diameter specimens), and in Nodular Limestone (54 mm versus 75 mm diameter specimens), there is an apparent inverse relation of strength to specimen size, while results from Biolithic and Disseminated Argillaceous Micrites show the normal relationship of decreasing strength with increasing specimen size.

A larger number of tests on uniform samples would be required to substantiate relationships of uniaxial compressive strength with either water saturation or specimen size.

5.3.6 Uniaxial Tensile Strength

Values of intact uniaxial tensile strength of four lithologies were obtained by three different tests performed on dry and saturated specimens parallel and perpendicular to bedding. Average values are given in figure 30. The direct-pull and Brazilian tests provide similar results, while four-point bending tests (performed only on Aphanitic specimens) gave tensile strength values approximately three times greater.

Direct pull tests as well as Brazilian tests clearly indicate that tensile strength parallel to bedding is greater than perpendicular to bedding. The Brazilian test results in addition show that water saturation reduces strength.

Direct Pull tensile strength of Biolithic Limestone parallel to bedding is greater than tensile strength perpendicular to bedding (6.52 MPa versus 5.46 MPa). Tensile strength of Aphanitic Limestone, measured on nine specimens perpendicular to bedding, is 5.55 MPa. Coefficients of variance are moderate for all three groups of pull-tests (up to 58%).

Brazilian tensile strength parallel to bedding of dry Biolithic limestone, based on four tests is 6.89 MPa. Average tensile strength for saturated Biolithic Limestone is lower both for specimens parallel to bedding (5.97 MPa, eight specimens), and perpendicular to bedding (3.78 MPa, two specimens). Brazilian testing was performed on only two Aphanitic specimens. Tensile strength parallel to bedding and dry is 5.92 MPa, while perpendicular and saturated is

3.35 MPa.

Tensile strength of Aphanitic Limestone determined by the Four-Point Bending test to be 15.33 MPa parallel to bedding and dry, is much greater than tensile strength determined by either direct-pull tests or Brazilian tests.

Tensile strength of two lithologies, Nodular and Disseminated Argillaceous Limestone, were obtained only by means of the Brazilian test. Tensile strength of Shale and Shaly Limestone was unobtainable because the weak nature of these rocks precludes specimen preparation.

Tensile strength values of Nodular Limestone parallel to bedding are slightly higher for dry specimens than for saturated samples (σt_{dry} = 3.65 MPa versus σt_{sat} = 3.48 MPa). The average tensile strength of Disseminated Argillaceous Micrite is 4.31 MPa for dry specimens parallel to bedding and 2.85 MPa for saturated specimens parallel to bedding.

5.3.7 Triaxial Compressive Strength

Triaxial compression tests were conducted on dry specimens of Biolithic, Nodular and Disseminated Argillaceous Micrite and on water saturated specimens of Aphanitic Limestone. Mohr envelopes were drawn for each lithology type using the results of the triaxial testing and values of uniaxial compressive and tensile strengths. Direct-pull tensile strength was utilized for Biolithic and Aphanitic Limestone, while Brazilian tensile strength was used for the Mohr envelopes for Nodular and Disseminated Argillaceous Micrite. Uniaxial compressive strength values for the Mohr Envelopes were determined from those uniaxial specimens most similar in size and lithology to the triaxial test specimens. The Mohr Envelopes for the four lithology groups are shown in figures 39, 40, 41 and 42.

Massive Crystalline Limestone is seen to be the strongest rock in all ranges of stress tested. Biolithic Limestone is stronger than Aphanitic Limestone at low normal stress. The cohesion intercept is approximately 17.8 MPa for Aphanitic Limestone while for Biolithic Limestone the smooth convex nature of the envelope makes estimation of a cohesion intercept very imprecise (see figure 39). The Mohr Envelope for Biolithic limestone is slightly concave downwards, indicating increasing plastic behavior at higher normal stress. Similar behavior is noted in the curve for Aphanitic Limestone, although lower normal stresses were attained during testing. The amount of axial strain recorded at failure is similar at similar levels of maximum principal stress, for the two lithologies (maximum axial strain recorded was 0.75%).

The triaxial test results on Nodular Limestone are variable and the Mohr Envelope therefore can not be drawn with confidence. Strength at low confining stress appears similar to the strength of Disseminated Limestone. At greater confining stress the Nodular Limestone specimens appear stronger (with some specimens much stronger) than

Disseminated Limestone. The cohesion intercept for Nodular Limestone is approximately 10 MPa, and for Disseminated Micrite it is about 8.9 MPa. Axial strain of specimens at failure is much greater in Disseminated Micrite (as much as 1.42%) than in Nodular Limestone. This highly plastic behavior is reflected in the concave, and at high confining stress, flat Mohr Envelope for Disseminated Micrite (figure 41).

5.3.8 Double Shear Test

Double shear testing of Biolithic and Aphanitic Limestone provides values of cohesive strength that are similar to those derived from triaxial testing. Eight double shear tests were performed on dry Biolithic Limestone specimens. Cohesion perpendicular to bedding is 8.83 MPa. (One additional test perpendicular to bedding produced an anomalously high cohesion value of 17.1 MPa.) Average cohesion parallel to bedding, measured as 15.2 MPa is significantly greater.

Eight double shear tests carried out on dry Aphanitic Limestone resulted in 10.6 MPa cohesion perpendicular to bedding and 17.6 MPa cohesion parallel to bedding.

5.3.9 Rock Deformability

Figure 43 presents a table of deformation moduli determined for Waterways Formation rocks. The modulus of deformation (E) and Poisson's Ratio (ν), calculated using electrical resistance strain gauge measurements, were determined for two specimens of Biolithic Limestone, specimens of Disseminated Argillaceous Limestone and specimen of Nodular Limestone (medium clay content).

The two moduli of deformation values for Disseminated Micrite are relatively uniform. The average, 11,410 MPa, indicates a rock of moderate deformability. Figure 44a and 44b reveal the regularity of strain in the two specimens. Lateral strain becomes increasingly greater, especially for specimen #100f. As a result, Poisson's Ratio increases with increasing axial stress, especially near failure, where readings are not able to reflect true deformations. Poisson's Ratio in specimen #98b increases from 0.07 initially to 0.11 at 50% ultimate load. In specimen #100f Poisson's Ratio increases from 0.06 to 0.15. The rapid increase of Poisson's Ratio and its relatively low values at 50% ultimate load are due to the content of clay (about 27%) which permits moderate axial compression with only minor lateral expansion.

Figures 45 and 46 show the stress-strain curves of two Biolithic Limestone specimens, #45b and #49a. One or both of the vertical strain gauges on specimen #45b were defective and axial strain measurements are not valid beyond the initial readings. The Biolithic Limestone specimens are much more stiff than Disseminated Limestone. Axial strains are regular while lateral strains reveal a slight acceleration compared with the regularly increasing axial strain, and

Poisson's Ratio behaves irregularly. In specimen #49a, strain values averaged over the entire range of axial stress were used to determine the deformation modulus (44,550 MPa) and Poisson's Ratio (0.24). In specimen #45b, the initial value of the modulus of deformation is high (62,930 MPa), and the initial value of Poisson's Ratio (0.32) is also high.

The one specimen of Nodular Limestone (figure 47) recorded valid initial measurements of strain, but at about 50% ultimate load the specimen partially fractured (sufficiently to reduce the applied load), and strains measured at greater stress do not appear valid. At 50% ultimate load the deformation modulus is 23,650 Mpa and Poisson's Ratio is 0.13. Figure 48 and figure 49 reveal the variation of moduli with axial stress. In some of the cases noted (specimens #45b and #82d), the point of fracturing or failure of the strain gauges can be noted on the graph. Figure 50 shows a more constant variation of moduli with stress in the specimens of Disseminated Micrite. The strain gauge method of measuring strain may be invalid for Nodular Limestone because of inhomogeneous strain in the hard nodules and the soft matrix. The modulus of deformation is high in comparison with Disseminated Micrite, which is of similar strength, and this suggests that the measured strains are not representative.

Four creep specimens of Aphanitic Limestone provide values of the deformation modulous ranging from 31,035 MPa to 46,345 MPa (figure 51). Axial strains were measured by dial gauge on the specimen platens and so modulus values are less accurate than those determined by more precise methods.

Only one of the four Aphanitic Limestone specimens subjected to creep testing revealed that creep was occurring. Two of the specimens failed during loading or shortly after loading. One specimen failed after eight days and showed no tendency to creep. The fourth specimen was carefully loaded in small increments, with each incremental axial load applied after certain that the previous level of stress had become very small. The stress/strain curve of this creep test has been modified to reveal separately the specimen strain due to creep (figure 52). Initial loading is shown as instantaneous. The incremental loads applied continually throughout the test are shown all together as a final load. The central portion of the graph reveals that this specimen underwent only a small amount of creep (about 300 um/m in 146 days) and therefore is not a plastic rock as defined by Coates (1965). It is believed that for all limestones of the Waterways Formation, creep under conditions of small confining stress would be small and not significant for considerations of deformation in excavations. With high confining stress at great depth in the earth these limestones would perhaps be subject to important amounts of creep.

5.3.10 Point Load Indices

Field Point Load indices of Waterways Formation rocks in many cases are misleadingly high because of incomplete cementation and the presence of clay.

The Massive Crystalline lithologies encountered and point-load tested in outcrop were little weathered and well cemented and cohesive along and across bedding. Test results therefore indicate very strong rock. For Biolithic Limestone Tdp5 perpendicular to bedding ranges from 2.1 to 4.4 MPa. Average Tdp5 is 3.00 MPa. For Aphanitic Limestone, the point-load index Is is 2.5 MPa parallel to bedding.

Most other lithologic types of the Waterways Formation have weathering patterns that prevent representative sampling for Point Load testing. Three examples which show the difficulty of determining Tdp5 from the field point load testing are presented in figure 53 (53a shows a poor relationship between fracture area and load, 53b shows no relationship between sample thickness and load, but 53c shows a good relationship of area to load).

Shale units did not occur in any of the four outcrops studied and no shale specimens were point load tested. Casual observations of outcropping shale indicated that the shale was highly weathered and extremely weak. Disseminated Argillaceous Micrite was not encountered in outcrop.

Nodular Limestone units weather to rubble composed of hard nodules surrounded by very soft clayey material. In high-clay Nodular Limestone, it is not possible to obtain representative field samples for any type of test. In low-clay Nodular Limestone, it is possible to obtain more-or-less representative samples, but of a size too large for Point Load testing (about 10 cm across, or larger). One Nodular Limestone unit field point-load tested, provided no meaningful results.

Shaly Limestone tends to weather to lenses or plates of hard crystalline limestone separated by lenses or thin layers (usually one cm. thick or less), of soft, highly weathered, clayey material which is not Point Load testable. Therefore representative sampling is not possible. Some broken pieces of Shaly Limestone are moderately weathered because of their (generally low) clay content and because their large surface area promotes weathering. Other platy pieces of Shaly Limestone can be poorly weathered crystalline limestone, and very cohesive. Field Point Load measurements reflect this variation from weak to moderately strong. Point load strength (Tdp5) perpendicular to bedding ranges from 1.4 to 3.0 MPa. Average point load strength is 2.3 MPa. The point load strength parallel to bedding was not determined because it was observed that values would fall into two groups: zero or extremely low when broken along shaly laminations, and very high when broken through the crystalline limestone lenses.

5.3.11 Impact Toughness Indices

Impact Toughness testing indicates that Massive

Crystalline Limestone is the toughest, Nodular Limestone less tough, and Disseminated Argillaceous Limestone the weakest. No other lithologies were tested.

Two groups of Aphanitic Limestone, composed of nine and six specimens, record Impact Toughness Indices of 7.67 and 6.5. Overall average index is 7.27.

Nodular Limestone was tested in four groups of nine, nine, one and four specimens. Recorded average Impact Toughness Indices for each group are 6.1, 6.0, 4.0, and 5.5. Overall average is 5.87.

One group of two specimens of Disseminated Argillaceous Micrite produced an Impact Toughness Index of 4.5.

5.3.12 Slake Durability

The Slake Durability of Waterways Formation rocks is high except for very weathered rock and for shales (figure 54).

Fresh samples of Massive Crystalline Limestone were not slake tested because their slaking resistance was visually estimated to be higher than the slaking resistance of Nodular Limestone (greater than 90%). Slake testing was performed on very weathered Biolithic Limestone. Two core samples that had been air dried for five years (with large variations in relative humidity) provided Slake Durability indices of 5.7% and 26.8%.

Ten Slake Durability tests were performed on fresh and on weathered core samples and on partly weathered outcrop samples of Nodular Limestone. Clay content of the samples was low or medium. High Slake Durability indices for the outcrop samples suggests that weathering in outcrop of low-clay Nodular Limestone does not affect the nodules and only partly affects the clayey matrix. Low-clay and medium-clay Nodular Limestones have similar slaking resistance and their combined average Slake Durability index is 93%. The Slake Durability Index on very weathered Nodular Limestone, cored from near the Devonian surface, is 38.7%.

Disseminated Argillaceous Micrite samples from fresh core have a very high average Slake Durability Index of 88.9%.

Fresh, banded Shaly Limestone from core has variable slaking resistance depending on the relative amounts of hard limestone and of soft shale in the specimens. Slake Durability Indices range from 49.6% to 92%. One sample of dessicated Shale (air dried for five years) recorded a Slake Durability Index of 23%.

There are two probable limitations of the Slake Durability Test for argillaceous limestones of the Waterways Formation, which cause slake indices to be too high. The great difficulty of obtaining representative samples of Nodular and Shaly Limestones is the most obvious limitation. Weak lenses and bands of soft argillaceous material tend to crumble and form fragments too small to be included in the specimen. Also argillaceous material surrounding nodules or lenses partly flakes off during sample preparation.

The second limitation is that argillaceous material that is included in the test specimens appears to undergo a hardening reaction when oven dried. Hardening occurs when some plastic clays are dried, and the clay minerals in these argillaceous limestones may act in the same way to increase cohesion and reduce slaking.

Waterways Formation slake indices determined for highly weathered rock, for Massive Crystalline Limestones and for Shales are judged to be representative. Measured slake indices for Nodular, Disseminated Argillaceous and Shaly Limestones may be high by 5% to 20%. A slaking index of 85% is classified as medium high. The only Waterways Formation rocks having poor slaking indices are shales and very weathered or dessicated rocks.

5.3.13 Rock Swelling Properties

Instrumented rock swelling tests were carried out on three specimens of Shaly Limestone and Shale. Specimens of other lithologies were not observed to swell significantly and were not tested.

One Shaly Limestone specimen was observed to swell axially by 1.24% in a Free Swelling Test (figure 55). A second Free Swelling Test performed on a specimen of Shale, recorded 9.0% axial swelling. In a Confined Swelling test performed on the same Shale, a low swelling pressure of 5.7 KPa was generated (figure 56). The discrepancy between the important amount of free swelling in the shale and the very low pressure of confined swelling is explained by the fact that the clay layers are readily squeezed laterally during confined swelling. The 9% swelling is important and under confined underground conditions could generate problems of rock squeezing and of pressure on tunnel supports. Therefore confined swelling tests should be performed on shale specimens under conditions of axial and lateral confinement.

5.4 Weathering Effects on the Waterways Formation

Weathering always reduces the strength of a rock mass, both along joints and in the intact rock. Weathering of the Waterways Formation ranges from very faint to extreme. Because primary porosity and permeability are low in the Formation, weathering has occurred along bedding and joints and from there progressed into the intact rock.

Weathering softens the rock surfaces of joints and reduces the extent and strength of the cement. Surface asperities become weaker and reduce the peak shear strength. Formation of low shear strength clay minerals along the joints facilitates shearing of asperities and reduction of the residual as well as of the peak shear strength of the joint.

The main effect of weathering in Waterways Formation rocks has been the reduction in extent of cementation rather than chemical alteration and formation of new clay minerals. The clay distribution in the Formation is in layers resulting from primary deposition. Bedding planes generally occur along argillaceous, poorly cemented layers and thus are subject to rapid weathering. Joints are reduced in shear strength only where they occur in highly argillaceous layers. Joints in Waterways Formation strata were not observed to contain secondary clay infilling. All joints encountered in fresh core were coated with bitumen which may have inhibited weathering.

In the intact rock, weathering weakens the cement. Weathering proceeds more rapidly in the argillaceous rocks. In the Massive Crystalline Limestone, weathering has been very faint and intact strength appears unaffected.

Overall, weathering effects on the Formation are moderate. Bitumen impregnation, discoloration and rock softening are noted along joints and fractures as deep as 30 metres below the Devonian erosional surface (plate 13). Weathering close to the erosion surface can be extreme, resulting in friable and hand-breakable rock (plate 14). The extent of this extreme weathering is generally less than one metre thick. From core evidence, weathering will not present a hazard for stability of openings. Some increase in permeability may be anticipated as a result of weathering close to the Devonian surface.

5.5 Intact Properties of Waterways Formation Lithologies

A large variation of strengths between specimens of the same rock type is apparent, but allowing for this it is possible to conclude that intact strength of all unweathered rock types except shale, is sufficiently great to present no problem for engineering construction. Discontinuity features become the overriding concern for the strong intact rocks while for Shale, both discontinuities and intact strength (and weathered intact strength) are important.

6. KARSTING IN LIMESTONE

6.1 Introduction

Karst is an erosional process involving removal of rock by aqueous dissolution. Karsting has taken place in the Oil Sands Region and has affected the Waterways and other Formations. There is evidence of deep karsting and removal of salt and evaporites from the Prairie Evaporite Formation and associated subsidence of overlying strata. There is also evidence of karst activity in the Waterways Formation. The effects of mining or construction on surface or underground in karstified rock can be severe and it is believed that an investigation is necessary. This chapter presents a summary of karst and a discussion of the extent of, and problems posed by, karst in the Waterways Formation.

Karsting is not restricted to limestone, but 80% to 90% of the earth's karst regions are in limestone and limestone results in the most numerous and conspicuous karst phenomena. Karsting proceeds more rapidly in rocks such as halite, gypsum, anhydrite or other evaporite rocks which are more soluble than limestone. The discussion in this chapter deals mainly with limestone and only brief reference is made to karst in evaporites.

6.2 Aqueous Corrosion of Limestone

6.2.1 The Corrosion Process

Karsting in limestone is the process of dissolution and removal of calcite by water. Dissolution, which acts on the molecular scale, can result in variable forms in the limestone involving small features on the surface of the rock, large earth-surface features or underground caves.

Dissolution of calcite by pure water is a slow process, but groundwater and even rainwater carry acids which enhance the corrosive power of the water. Some atmospheric carbon dioxide is absorbed by rain and forms carbonic acid. As the rain percolates through soil, it absorbs much more carbon dioxide, especially in the upper, aerated soil layers. In addition, bacterial activity, the rotting of vegetal matter and solution of inorganic chemicals in the soil, produces soluble organic and inorganic acids. Thus dissolution of limestone is carried out by three means:

1. carbonate dissolution by pure water
2. bicarbonate dissolution by carbonic acid
3. dissolution by dissolved organic and inorganic soil acids.

The first two processes are reversible while the third is irreversible.

Carbonate dissolution results in equilibrium between the water, the calcite and the dissolved ions:

$$CaCO_3 \rightleftharpoons Ca^{++} + CO_3^{--}.$$

When CO_2 gas is absorbed by water, the highly soluble

$Ca(HCO_3)_2$ forms, which exists only in aqueous solution. The corrosive power of water increases with the amount of dissolved CO_2. The amount of CO_2 content of water is controlled by:

1) the partial pressure of CO_2 in the atmosphere
2) the temperature of the solvent and gas
3) the hydrostatic pressure
4) the time available.

Dissolution of limestone by other agents may result from the aerobic decay of organic matter in the soil and from the activity of soil microorganisms which produce formic, fulvic, crenic, oxalic and acetic acid as well as carbonic acid and other acids and secretions. Inorganic acids and salts in a weathering soil may include sulfuric and nitric acids. Sulfuric acid can result from weathering of pyrite and marcasite.

In addition, Bogli (1964) suggests that mixing of different waters both saturated with calcium carbonate (and therefore individually non-corrosive) results in renewed corrosive abilities. This is known as mixture corrosion.

6.2.2 Factors Affecting Carbon Dioxide Content of Water

Four factors affecting carbon dioxide content, as listed in the previous section, are discussed. The carbon dioxide content of the soil atmosphere is extremely sensitive to the type of plant cover and even to plant species, so that although the rate of corrosion partly depends on the amount of precipitation, it is to a greater extent determined by biological soil activity and the process of evolution of the soil layers.

The time available for absorbtion of carbon dioxide by the water depends on the permeabilities of the bedrock and the soil, the groundwater base level and gradient, the plant cover, and rates of precipitation and evaporation.

Where humus is thick, there is more biological activity, wider variety of organisms, greater water storage capacity, less aeration, more uniform release of water into the underlying rock, and more prolonged contact, all of which enhance carbon dioxide absorbtion by the percolating surface waters.

Lower temperature, in accordance with Henry's Law, allows more carbon dioxide to be absorbed by water. Tropical rains and groundwater for instance, are less able to absorb carbon dioxide than the colder waters of the temperate and arctic climatic zones. However higher temperatures accelerate the actual dissolution process and the greater organic and biological activity in the tropical soil entails much greater production of both carbon dioxide and organic acids.

With increasing depth and greater hydrostatic pressure, there can be an increase in the amount of absorbed CO2 in Karst groundwaters. Jakucs (1977, page 233) states that the increase of hydrocarbonate dissolution potential of Karst water resulting from increased pressure occurs in the initial increase to approximately ten atmospheres. Greater pressures have a much lower influence on the direct intensity of dissolution.

6.3 Rock Features Affecting Karst Erosion

The process of limestone corrosion is determined by characteristics of the limestone as much as by features of the karst waters. Important characteristics of the limestone include texture, porosity, the presence of contaminants, and structural and physiographic features of the limestone strata.

Slight textural differences and differences of porosity can have great effects on the dynamism of dissolution. Crystallinity and lattice structure may significantly alter theoretical predictions based on mineralogy. For instance, aphanitic limestone with very low porosity and conchoidal fracture is much less soluble than crystalline limestone. On the other hand, highly porous limestones may diffuse the corrosive potential throughout a rock and inhibit karsting. If porosity is restricted to joints, then solution can be initiated and developed in discrete locations.

Clay and non-soluble minerals in limestone impede dissolution and can accumulate and clog cavern passages. Drainage in well bedded limestone may occur dominantly along bedding planes where most of the contaminants in the rock occur, so that karst corrosion is inhibited.

Dolomitic rock essentially behaves similarly to limestone, but has been less investigated. Magnesium carbonate occurs in three mineral forms and behaves in a complicated manner. Magnesia in water can increase solubility of calcite.

Structural features of the limestone can have a profound influence on both underground and surface karst features. The number of open joints, fissures and bedding planes and their ability to transmit infiltrating waters, partially determines whether karst activity will be initiated and the depth at which it will occur. Lack of jointing may prevent karsting. Jointing may also weaken a rock mass enough to prevent cave development.

Direction of jointing can sometimes be seen to control the alignment of karst features. Faults often affect the location and direction of karst development because they significantly influence groundwater flow and fracture patterns. Gilewska (1965) suggests that karst always develops under humid conditions (warm or cold) following phases of earth movement, because tectonic activity produces a high relative relief and a well developed jointing system.

6.4 Surface Features of Karst

The effects of karsting can be separated into features on or near the earth's surface and underground features. Amongst the surface features one can distinguish between the relatively small and superficial features, generally developed on bare surfaces; and large-scale geomorphological features.

Amongst the surface karst features discussed in the following sections are dolines and karst valleys. Surface geomorphological features from the tropics are distinct and will be presented in a separate section (6.7.7) on tropical karst.

6.4.1 Superficial Karst Features

The whole complex of microkarst forms that develops on outcrop surfaces or under a thin moss or soil cover, is known as karren or lapies. Karren vary in size from a few mm to one to two metres. Karren may develop on limestone in isolation, without development of large scale karst features. They have no significance for underground mine development.

6.4.2 Dolines and Swallow Holes

Dolines, or sink-holes, are closed surface hollows of moderate dimensions generally circular or elliptical in plan, through which water penetrates the bedrock and where solutional erosion of the limestone occurs. Dolines are the basic karst form in temperate and northern climates. The province of Montenegro, Yugoslavia has 64% of its land surface formed of dolines. The different types of dolines are: solution dolines, alluvial dolines, solution collapse dolines and collapse dolines (figure 57).

In solution dolines, water infiltrates along joints and causes solution. As the joints are enlargened by solution, the ground surface lowers and forms a closed hollow. Alluvial material deposited in the hollow aids the corrosive power of the seeping waters. The base of the hollow contains a mixture of weathered limestone blocks, residual soils and alluvial deposits.

In alluvial dolines, the Karst erosion develops in limestone beneath a thin cover of rock or unconsolidated deposits. A subsidence cone forms in the overlying material as limestone below the contact is dissolved and removed. Alluvial dolines rarely develop where the overburden is greater than about 12 metres.

Solution collapse dolines form under large thicknesses of overburden. Dolines have developed in the Pennant Sandstone in south Wales, where solution occurs along the upper surface of limestone buried by as much as 150 metres.

Collapse dolines occur by breakthrough of caves to the surface. They are chimney shaped and have steep or vertical walls with a large depth to diameter ratio. They are oval or irregularly round in form with the base filled with a chaotic mixture of collapsed blocks.

Dolines may not form in arid and semi-arid climates because of the rapid surface erosion. In tropical Karst areas, dolines develop in a different manner and progress to completely different geomorphic features.

With the growth and development of solution and fluvial dolines, larger hollow areas called uvalas develop, which have undulating floors and irregular shapes. Swallow holes are drainage features which can develop independently or in the bottom of uvalas. They are openings through which active streams or rivers disappear underground. Sweeting (1972) distinguishes three types of swallow holes as those:

a) with little or no topographic expression (therefore are recent as they develop fairly rapidly into other forms)
b) associated with caves
c) associated with vertical holes or shafts
d) formed in drift or alluvium.

Swallow holes generally are not found in dolines, where drainage is by seepage under the soil cover and where solution openings in the limestone are infilled with soil and rubble.

6.4.3 Karst Valleys

In highly karsted terrain, dolines replace valleys as the surface geomorphological feature that drains the surface waters. But in most other karst areas, surface features reflect a mixture of karstic and non-karstic processes. The most important non-karst process in temperate and tropical climates is fluvial erosion of valleys. Both processes of fluvial and karst erosion are able to promote and modify each other and surface drainage is likely to be intermittent, disrupted, widely spaced or absent.

Valleys may take several forms in a karst terrain. Allogenic valleys are through valleys which cross the entire karst region and contain rivers that are large enough not to disappear underground. They are generally canyon shaped, as there is strong vertical solution below the river which assists in sharply incising the allogenic river into the landscape. Parts of the allogenic valley may be formed by collapse into former underground rivers and in these areas natural arches and caverns are likely to be found.

Blind valleys and pocket valleys are only 'half valleys', which are developed in either their upper or lower halves, respectively. A blind valley forms when a river in a normal valley crossing karst terrain suddenly disappears underground. A blind valley is best developed when water flows down a normal valley onto karst limestone and then disappears, often into a cliff with a cave as the point of entrance. A pocket valley is formed by a river which issues from underground, often from caves at the base of a cliff.

Dry valleys, having no surface flow or only seasonal flow, are common in karst terrain. Many are related to past drainage systems developed in overlying strata and subsequently cut down into karsting limestone.

In established normal valleys, swallow holes may develop because of the added solutional capability offered by thicker soil cover and large volumes of percolating water.

6.5 Caves

Caves are initiated along those joints having greater hydraulic gradient and larger initial opening, so that only a few of the original fractures of a limestone mass will become enlarged into caves. If discharge through a joint is sufficient, turbulent flow and mixing of different waters can occur, allowing the powerful solution by mixture corrosion (section 6.2.1). Five mm is considered by Jennings as the threshold of cave development because at that size turbulent flow is possible. Suggestions as to the actual process initiating dissolution along a joint and growth into caves include preferential solution around sulfide minerals, oxidation by bacteria or mixture corrosion.

Formation of caves deep in the earth can be partly attributed to mixture corrosion, resulting from mixing at depth of different karst waters, and partly to increase in hydrostatic pressure which allows greater carbon dioxide content and increased corrosive power of karst water at depth.

Renault (1960) also adds temperature fluctuations as a process aiding in deep solution in temperate climates. In winter the cold surface water dissolves calcite which it precipitates at lower and warmer depths. With precipitation and deeper penetration the water again becomes aggressive. Mixing of seasonal waters of differing temperatures can also result in mixture corrosion, according to Bogli.

Some factors which influence the formation and development of caves are:

1) the form of the primary capillary
2) the petrological and chemical characteristics of the limestone
3) structure of the limestone - dip, jointing, bedding, faults
4) the type and amount of water flow through the rock (whether it is forced flow - phreatic, or free flow - vadose)
5) regional physiography of the area
6) history of the cave
7) climate and past climatic variations
8) influence of cave deposits.

The most important of these features are the character of the limestone, the type of water flow, the regional physiography and the climate. According to Sweeting (1972), caves do not form at a particular stage of karst development, but only when conditions which favor their development exist. Karsts can exist without caves. Caves often are strongly controlled by structure such as bedding, jointing, faulting and folding.

6.6 Karst Hydrology

There is still dispute as to the mode of formation of caves. The watertable and the channel flow theories are dominant. Four vertical hydrodynamic zones of karst water can be distinguished (figure 58):

a. the zone of aeration - water percolates downward; perched water tables may result

b. the zone of seasonal fluctuation - the zone of transition between the zones of aeration and full saturation

c. the zone of full saturation - drainage is governed by the local drainage network

d. the zone of deep circulation - groundwater is not influenced by local drainage; water movement is very slow.

A mature karst hydrogeology has many independent and complicated net-like systems of passages and chambers. Where free intercommunication is not established between flow networks, there may be no common watertable. In the degenerate stage of karst hydrogeology the rock becomes riddled with passages and a stable water table will be developed.

6.7 Classification of Karst

Historically there has been much discussion concerning the classification of karst. Possible methods involve structure, climate, or the relation of the features to overlying materials and the earth's surface. The many factors influencing karst development make classification difficult. Much emphasis was inappropriately placed on the evolution of karst landforms, because researchers accepted the cyclic theory that one landform or one type of karst always progresses to a more mature type. Karst researchers in central and western Europe have emphasized the classification of karst solely on climate, whereas researchers in other parts of the world have also considered other factors in their systems of classification (such as bedrock structure and physiography).

6.7.1 Classification Systems

The system of classification according to structure divides karst into Mountain karst, which develops in structurally and topographically deformed regions, and Lowland karst, which forms in plains where stratigraphic dips are small and regular. This method of classification is not able to account for the great variability of karst forms.

Classification according to relation to the earth's surface and to climate are discussed in 6.7.2 and 6.7.3. Other, rare types of karst such as pseudo karst and thermal karst are generally classified as 'exotic'.

6.7.2 Classification By Relation to the Earth"s Surface

Types of karst in this system are: 1) bare karst 2) covered karst 3) interstratal karst and 4) fossil karst.

The term 'bare karst' was used by early karst researchers to describe some karst terrains in southeastern Europe where there is little or no soil cover. However these karsts were not developed under a bare surface; the land surface is now bare because of climatic changes and cultural impact. Use of the term 'bare karst' in Europe is not valid.

Covered karst includes a wide variety of karst types developed in rock covered by soil, unconsolidated material, or thin non-karstic rock overburden.

Interstratal karst develops in limestone covered by thick non-carbonate strata and involves both the limestone and the overlying strata. Surface features developed are mostly solution collapse dolines.

In New Mexico there has been interstratal karsting in limestone under 100 metres of sandstone. Collapse hollows with steep sides, which occur on the sandstone surface, are often filled with alluvium and are frequently the site of powerful springs. Cracks and fissures occur in the subsiding sandstone. At another location in New Mexico, collapse hollows forming deep lakes occur in thick sandstones overlying gypsum and limestone at depth.

Fossil karst is karst from an earlier geological time that has been later covered by sediments. Fossil karst may be presently exposed or it may still be covered by overburden. Formation of large karst depressions in Poland took place in the Tertiary when the climate was hot and humid. Fossil tropical karst landscapes are often connected with bauxite, [illegible] France, Montenegro and Greece. In Hungary, a fossil tower-karst is partly covered with bauxite.

6.7.3 Modified Classification According to Climate

Sweeting (1972) states:

> "Since there are numerous interacting causes, any one may override the influence of climate and give rise to a different type than that expected on a climatic basis."

Also, climate itself has changed greatly since Tertiary and Quaternary times. Classification on a climatic basis is the most useful, but one must expect many variations in land forms introduced by other factors. The type of karst considered in this classification are: 1) holokarst 2) fluviokarst 3) glacial and nival karst and 4) tropical karst.

6.7.4 Holokarst

Holokarst is a pure karst, where other erosional processes are of minor importance. Holokarst is best developed on the Dinaric coast of Yugoslavia. The landscape is a succession of funnel shaped dolines from a few metres to over 100 metres in depth, separated by conical hills with slopes of 20° - 30°. The limestone is more than 4,000 metres thick, mountains are 2,000 metres high, and rainfall is more than 2,500 mm per year. There are no surface streams and no river-formed features. Water circulation is very deep and caverns that will never be discovered probably exist at great depth. Clastic beds are lacking and as a result there is no fluvial material and no development of surface drainage.

6.7.5 Fluviokarst

Fluviokarst is formed by a combination of fluvial and karst processes. Fluviokarst areas have allogenic rivers and are therefore more compartmentalized into blocks. The vertical and lateral extent of the limestone is less than in holokarst and there is less opportunity for development of deep circulation irrespective of the hydraulic base level. Because of the presence of clastic sedimentary strata, fluvial erosional processes are encouraged, and normal river valleys are common, in addition to dry and partially developed valleys.

Fluviokarst has extensive caves, which tend to form at the junction of the karsted limestone with the less permeable, non-carbonate strata. Caves are associated with the development of allogenic rivers and thus are often arranged in a series of levels related to fluvial erosion stages. Caves are large and may have collapse features when near the surface . Fluviokarst has thick soil horizons developed on the fluvial deposits originating from the non-carbonate strata.

6.7.6 Glaciokarst and Nival Karst

These types of karst are produced by the karst action of melting snow and glaciers combined with glacial erosion processes. They occur in glacial and periglacial areas of the arctic or high mountains.

Nival karst, which results from melting snow, often forms dolines. Glacial scour and glacial erosion is the main non-karst process in glaciokarst and glacial debris is abundant. Caves and vertical chasms are characteristic of glaciokarst. One type of karst developed in complete permafrost that is found in Greenland, the Canadian Arctic Islands and some other arctic locations, has no underground circulation and no caves. Karst features exhibited are mainly micro-karren. In discontinuous permafrost areas, there can be some underground circulation and a few small caves may develop.

6.7.7 Tropical Karst

Tropical karst appears geometrically to be an inverted form of temperate karst because isolated towers and cone-shaped hills tend to be superimposed on the flat plane formed by the low terrain between the uplands. Corrosion is mainly near the surface below the flat alluvial lowlands or swamps. Rapid evaporation and precipitation in the uplands cause case-hardening of the remanent hills so that a hard crust forms on their tops to partially protect them from active karst erosion.

Solution furrows 10 metres deep are common in tropical karst but corrosion at depth is less common and deep caves are rarely found. The seasonal temperature changes in the atmosphere and the groundwater are small and offer less possibility of mixing of differing groundwaters and hence mixture corrosion at depth is less likely. Also, redeposition of calcium carbonate tends to seal joints and prevent entry of waters deep into the earth. Caves are small and tend to be networks of small tunnels. Large caves are mainly due to erosion by allogenic rivers near the surface.

Tropical karsting has several distinct features associated with the high biological and vegetational activity. Because the tropical waters are warm, they dissolve limestone more rapidly but are also rapidly saturated with CaCO3 and calcite is redeposited. Large concretionary stalactites and stalagmites are therefore common. Because of rapid solution and redeposition, the amounts of CaCO3 carried in the water and its pH varies quickly.

Thick soil horizons with abundant tropical vegetation develop in the tropical climate, and rivers flow on the ground surface, so that fluvial erosion is important. Solution is controlled by bacteria and other micro-organisms which accelerate corrosion beneath the broad swampy floodplains, or beneath the floors of undulating hummocky areas known as 'cockpits'. Thus corrosion takes place near surface and develops laterally. All of these processes tend to dissect the karst areas into isolated mounds or towers and pinnacles (inselbergs), separated by swamps or slow moving rivers. However in tropical and subtropical desert areas, rapid runoff creates gulleys and closed hollows are uncommon. A calcrete, or caliche, forms on the surface of the limestone.

Tropical karst can be divided into two types:

1) Cone Karst (Kegelkarst) - develops cones and hummocky areas, and

2) Tower Karst (Turmkarst) - develops towers and pinnacles.

Cone karst forms rounded hills, which are often 100 to 130 metres high and up to one kilometre in diameter. Cone karst has developed in Yunnan, China on a limestone sequence continuous from the Proterozoic to the Quaternary. Lack of symmetry noted in cone karst may be due to bedrock structures or may even be due to variable amounts of rainfall carried onto one side of the hills by the prevailing winds.

Tower karst develops where alluvial deposition is rapid and flat flood plains are formed. The water table is generally just at the base of the towers, where springs issue and collapse caverns and undermining of slopes often occurs. There is little corrosion in the hills because of surficial case hardening, but much at their base and below the alluvial plane. The lowering of the plains is limited by the water base level. The extensive tower karst developed in Yunnan-Kweichow was assisted by tectonic uplift associated with the Himalayan orogeny. It is possible for cone karst and tower karst to grade into one another.

6.8 Karsting and the Waterways Formation

Three effects of karsting in the Waterways Formation can be distinguished:

1) Regular subsidence
2) Massive collapse
3) Formation of cone karst (fossil, buried karst, with effects mainly on the ancient erosional surface).

Regular subsidence of Waterways Formation strata is believed to be due to solution and removal of salt from the Prairie Evaporite Formation. Salt removal has been inferred from drilling data, and gentle folding of Waterways Formation strata into basin and dome structures observed in outcrop, suggests widespread subsidence.

Massive collapse of strata into solution collapse holes and large caverns formed by salt solution has occurred (a conceptual diagram is shown in figure 59). Large collapse zones can be as extensive as the Bitumount Basin which is 15 kilometres in diameter. There are also small depressions in the Devonian surface which are assumed to be solution collapse dolines (collapse holes). Near the Devonian unconformity these holes have been filled with coarse McMurray sediments or, in one case, with glacial till. These collapse holes would be difficult to detect and avoid during mining because of their small size.

One small collapse hole encountered during drilling by Suncor was less than 50 metres across and contained sandy fill to a depth of at least 50 metres. Investigators who have encountered holes of similar dimensions have concluded that walls are nearly vertical. Gorrel (1976, page 67,73) suggests that salt solution and development of collapse structures began during the Devonian Period and is still continuing, and that karst-like topography on the present-day surface seems more widespread to the east of the Athabasca River. Drilling has shown that solution has removed nearly all salt from the Prairie Evaporite Formation to the east of the Athabasca River but only partially to the west (see cross-section, figure 3).

The extent of a buried cone karst on the ancient erosional surface of the Waterways Formation is unknown. One occurrence of possible cone karst has been reported from outcrops of platy micrite limestone of the Christina Member near the mouth of the Christina River (M. Dusseault, PhD Thesis, University of Alberta, 1977). Karst domes (sometimes capped with red paleosol) are separated by non-fluvially eroded channels with a maximum depth of 7.5 metres. The channels or chimneys were filled with coarse clastics and argillaceous sands of the basal McMurray Formation. It is not possible to predict how deep the channels extend beneath the Devonian surface; 7.5 metres may be a maximum, although groundwater level during the time of formation probably determined this. Another possible occurrence of cone karst in an outcrop of Waterways Formation along the Steepbank River has been reported (Flach, personal communication, September, 1979). The descriptions of the Devonian erosional surface by Martin and Jamin (1963) are similar to descriptions of some cone karsts, with broad domes about one kilometre across with amplitudes of 100 metres and low dips of 5° - 25°.

The lack of concrete evidence thus far of other karst processes may indicate their absence; their existence can only be ascertained with further exploration. The most important karst process for underground mining, as has been stated, is cave formation.

Cave formation in Upper Devonian limestones in the Athabasca Oil Sands region is entirely speculative. No evidence has been encountered other than sand-filled fractures four cm wide in core, near the upper contact of the Woodbend Formation (see section 4.2.5). Tropical karsting of exposed limestones during Devonian time may have occurred, but cave formation is not a prominent feature of tropical karst. Caves might have been formed in the Waterways Formation as a result of interstratal karsting below.

In regards to karsting of Waterways Formation strata, some comments can be made concerning lithology and climatic and tectonic history since late Devonian time. The overall high content of clay in all members of the Formation would mitigate against karst development. The clay residue would block enlarged joints and channelways very soon after their initiation and prevent effective interconnected flow of water. The high clay content of most layers would mitigate against initiation of dissolution. Only Massive Crystalline Limestone has less than 10% non-carbonate minerals and a well jointed system to channel possible corrosive waters through the rock. In most cases these layers are not thick (2 to 3 metres). The slow downward percolation of surface waters through layers of varying clay content would be unsatisfactory for development of caves; redeposition at deeper levels of dissolved calcite could likely result because of altering groundwater chemistry during its slow passage through the Formation.

Climatic and tectonic changes have been dramatic in the 315 million years since the deposition of the Waterways sediments. Epeirogenic uplift of these sediments above sea level in the Pennsylvanian (315 million years ago) and again in the Early Tertiary (60 million years ago) would have brought about the flow through the Formation of surface-recharged groundwater and the ability to be karst eroded. Uplift since the deposition of Cretaceous sediments resulted in a situation essentially unchanged today: argillaceous limestones overlying more easily karsted evaporites. Direct karsting of Waterways Formation limestones is not visualized to have occurred in this period.

In the Pennsylvanian through Jurassic, during the first period of uplift, the Devonian strata were above sea level and were fluvially eroded. During this period of exposure there was some tropical karsting on the surface of the Formation (Dusseault, 1977). Although karsting may also have occurred within the Formation, it would have been competing (as at present) with the more easily karsted, underlying evaporites.

Little can be said of climatic influence on ancient karsting of the Waterways Formation. Climate would have had little effect on interstratal karsting. The climate during the Pennsylvanian-Jurassic period of exposure was tropical. This fact is complementary to the existence of a tropical cone karst. Also complementary to tropical karst is the lack of evidence of caves. Concrete evidence concerning caves can only be obtained by field investigation such as suggested in chapter eight.

7. THE GROUNDWATER REGIME

7.1 Groundwater Flow Systems

The very large volume of rock in the Athabasca Oil Sands region precludes detailed conclusions concerning the hydrogeology of the entire sedimentary sequence in this large area. No groundwater investigations were undertaken in this study. Groundwater investigations have been conducted by the Research Council of Alberta (Hackbarth 1977 and 1978, Hackbarth and Nastassa in prep.) and the Oil Sands Environmental Study Group (Gorrel, 1976). The Alberta Research Council is continuing its groundwater studies and is maintaining a groundwater well observation system (RCA 1976, 1977, plus yearly updates). The ERCB collects limited data on groundwater conditions provided by private companies about completed exploration wells. Several private groundwater studies of individual Oil Sand leases have been conducted by lease-holding companies, but these often do not have much data on the Devonian groundwater systems. Gorrel (1976) emphasizes the small amount of data by noting that of the more than 3,000 oil sand exploration and evaluation holes drilled by member companies of the Oil Sands Environmental Study Group, less than one percent penetrated Devonian strata far enough to provide geological or hydrogeological information.

A framework for the groundwater regime was provided by Hackbarth (1977), who proposed that regional groundwater flow occurs in three flow systems whose boundaries coincide with stratigraphic divisions. As shown in figure 60, these systems occur above the Precambrian strata, which are considered the groundwater basement, and comprise:

1. Cretaceous System - Oil Sands, sandstones and shales, and surficial deposits
2. Upper Devonian System - limestone, shaly limestone and shale
3. Middle Devonian System - limestones, evaporites and shales.

Hackbarth summarizes the groundwater flow as being mainly horizontal in the Cretaceous system, with discharge into the major rivers and recharge in the upland areas. Flow in the Upper and Middle Devonian systems is postulated by Hackbarth to be controlled by a major fault parallel to the Athabasca River. The fault permits the flow of Methy Formation water to the earth's surface and generates deep flow towards the fault from east and west of the Athabasca River. Away from the Athabasca River, flow in the Devonian strata is assumed to be horizontal.

Mine development in the Upper Devonian Waterways Formation is primarily concerned with groundwater flow in the Upper Devonian System, although possible interconnection with the other two systems must be investigated. Recovery of bitumen from the overlying McMurray Formation would require intensive study of the Cretaceous groundwater system.

7.2 Groundwater Flow in the Upper Devonian System

The Upper Devonian System is composed of the Waterways Formation and the stratigraphically higher Woodbend Group. These strata are lithologically similar and are all generally low in permeability (average <10 cm per second, Hackbarth 1978). According to Hackbarth, the hydraulic heads in the Cretaceous system are everywhere less than hydrostatic due to strongly horizontal flow in the horizontal strata. The occurrence of hydraulic heads that are greater than hydrostatic in the Methy Formation therefore indicates that a hydraulic gradient occurs through the Waterways Formation and this is consistent with the upward flow of salt springs from the Methy Formation.

The ability of the Waterways Formation to transmit water may be much higher in some locations because of karsting. The three karst or karst related processes that have occurred in the Formation , detailed in chapter 6 (section 6.9) are: regular subsidence, massive collapse and formation of cone karst.

Regular subsidence has caused flexure of Waterways Formation strata and opening of joints or creation of new fractures. The measured low transmissivity values of the Formation likely reflect the low porosity of the rocks. Transmissivity through joints, increased as a result of regular subsidence, could be much higher than the measured values.

Massive collapse would have caused extreme fracturing and greatly increased transmissivity of Waterways Formation strata and a risk of hydraulic connection to the highly saline waters of the Methy and/or La Loche Formations below. These two lower formations can be very permeable and are known to contain highly saline waters which have been reported as under sufficient hydraulic head to flow to the surface from drill holes (Carrigy 1959). Saline springs in the Athabasca River valley indicate that a fracture system through the Waterways Formation permits the flow of Methy waters to the surface (Gorrel, 1976 page 65).

Cone karst topography and weathering on the upper surface of the Upper Devonian limestones could alter groundwater flows along the Devonian/Oil Sands contact. Karst erosion below former lowland areas could result in a horizon of high permeability and facilitate lateral transmission of groundwater. Tunnel-shaped caves, which occur in tropical karsts near the bases of towers or remanent uplands, could result in local high lateral transmission.

The possible formation of caves in the Formation is the most catastrophic danger for underground mine development.

Karst formation of caverns containing pressurized water could result in dangerously high water flows into mine openings. The existence of caverns is only speculative and the possibility of intersecting a water-filled cavern during tunneling may be remote, but the size, location and nature of caverns would have to be determined and their drainage undertaken or tunnel detours made.

7.3 Mutual Impact of Mining and Groundwater

The generally low permeability of Waterways Formation and relatively low hydraulic gradients will result in low groundwater flows into excavations in these strata. Localized zones of high permeability such as those noted in section 7.2, could result in high water inflows from below (Methy Formation), from above (basal water sands of the McMurray Formation), or from caverns within the Waterways Formation (figure 61).

Areas in which subsidence and fracturing of Waterways Formation strata has occurred may be so widespread as to be unavoidable during mining. Indeed, all outcrop areas examined show evidence of gentle folding (plate 1). The increase in hydraulic transmissivity of a fractured rock mass is not known, but increased pumping requirements for mine drainage would result. The quality of mine waters resulting from inter-system flow through fracture networks in general would not be an environmental problem. The only formations known to contain highly saline waters are the deeply buried Lower Devonian Methy and La Loche Formations. Highly saline water from the Methy Formation (200,000 ppm chloride in one sample, Carrigy, 1959) could enter excavations in the Waterways Formation in faulted areas and present environmental problems for disposal. Hackbarth estimates that the total dissolved solids in the Waterways Formation should not be more than 10,000 mg per litre over most of the region. Bitumen recovery projects which involve drainage of the McMurray Formation or lowering of the water table in the Cretaceous strata could enhance the hydraulic gradient between the salt-rich formations at depth and the working levels, and increase the upward flow of saline waters into near-surface groundwaters and mine openings.

The Devonian strata generally act as a hydrological basement for local flow in the Cretaceous system, however downward flow of groundwater from the Cretaceous system into the Upper Devonian is a possible result of mine activity. The basal water sand zone of the McMurray Formation commonly occurs as a water-saturated aquifer up to 15 metres thick, with piezometric pressures equal to or greater than pressure in the surrounding Oil Sands. Intersection of water-saturated sands in openings, or by hydraulic connection to them by either drill holes or excavations, could result in large flows of water into mine openings. Hydraulic conductivities of the basal water sand can be higher than 10^{-2} cm per second, whereas the 'average' conductivity of the McMurray Formation is approximately 10^{-5} cm per second (Hackbarth, 1978).

Pre-drainage of the McMurray Formation during mining extraction of Oil Sands would greatly alter the distribution of fluid potential so that groundwater from surrounding areas of Cretaceous strata would discharge into a mining location.

The injection of hot steam or chemicals to mobilize the bitumen during in-situ extraction would place a major stress on the hydrogeological environment (Gorrel, page 25), including altering groundwater flow patterns, thermal pollution, pollution of acquifers by oil or chemical rich waters, and piping or blowouts to the surface where overburden thickness is insufficient. In addition, permeability will increase as bitumen is removed and numerical techniques would be needed to analyse the groundwater flow in the transient system.

8. EXCAVATION AND SUPPORT IN THE WATERWAYS FORMATION

Excavation in the Waterways Formation requires knowledge of the rock-mass and its environment. Previous chapters have provided information on the geotechnical properties of the rock mass. This chapter summarizes available information and makes preliminary conclusions concerning excavation methods and ground control (sections 8.5 and 8.6).

Section 8.2 considers possible virgin earth stress conditions. The specific geometric and strength properties of the Waterways Formation described in detail in chapters 3, 4 and 5 are utilized in three widely recognized rock mechanics classification systems (section 8.3) to provide an initial estimate of likely ground conditions. Mining experience in limestone of similar character is reviewed in section 8.4. Based on this information about ground stress and ground behavior, and on some applicable experience, section 8.6 identifies potential ground problems and possible methods of control. Section 8.7 describes topics requiring further study.

8.1 Rock Mechanics Information Needed for Mine Development

Neither this study nor previous studies were intended to be sufficiently comprehensive for the design of a specific project. Much of the information provided can, however, be applied to specific sites. This report can be used to assess regional regional factors that could affect excavations and as a basis of comparison or a point of departure for detailed and site-specific studies. A site specific study for the purpose of designing development and/or production openings in the Waterways Formation or other Devonian Formations would require a detailed investigation of six primary rock mechanics factors as follows:

1) large scale geological structure including geometry of the McMurray /Devonian unconformity
2) small and/or erratic geological structures
3) groundwater flow and pressures in the Devonian and in the basal McMurray Oil Sands, including drainage patterns along the McMurray/Devonian unconformity
4) rock discontinuities
5) lithologies and intact rock strengths
6) depth of ancient weathering below the McMurray/Devonian unconformity.

Large scale structures include geologic contacts (i.e 'top of Devonian'), large faults, dip of strata and folds. Locating these structures precisely will allow them to be avoided during excavation or to be considered in the overall design, layout and selection of mining and support techniques.

Geological structures such as karst caverns, collapse holes and small faults are difficult to locate because of their restricted size and unpredictable occurrence. The magnitude and extent of such features and possible difficulties and dangers associated with tunneling through them would have to be assessed for each site.

Groundwater problems in mining can be serious. The locations of acquifers above the working level(s) and their transmissivity must be known. Mine development and future bitumen extraction operations could have detrimental effects on the groundwater regime by, for example, pre-drainage of acquifers which would alter regional flow patterns and lower near-surface groundwater levels.

The pattern of rock discontinuity systems must also be studied, including their number, orientation, location and physical properties. The various lithologies to be encountered, their locations, thicknesses, intact strengths and weathering profiles must be known.

8.2 In-Situ State of Stress

Virgin stress magnitudes and orientations are not known in the Waterways Formation. Hydrofracturing experiments performed by oil companies have provided stress measurements in the McMurray Formation. Hydrofracturing of the Oil Sands requires knowledge of virgin stresses both for correct alignment of induced fractures and for control of their initiation, growth, maintenance, and limitation to the desired stratigraphic horizons. Hydrofracturing tests and other evidence from the McMurray Formation indicate that high horizontal stress does exist in these strata. Brooker, 1974 estimates that horizontal stress can be three times vertical stress at relatively shallow depths in the open-pit Oil Sands mines. However, virgin stress fields may differ between the McMurray and the Waterways Formations. Principal stresses in the Waterways Formation are expected to be oriented vertically and horizontally on a regional scale (or perhaps orthogonal to regional bedding which is near horizontal), as there have been no major geologically-recent tectonic events in the area.

The vertical principal stress under conditions of no active or remanent tectonic stress may be calculated as that stress resulting from overburden weight, and would increase linearly with depth. Areas where strata are subsiding into solution cavities may have a significantly lower vertical stress. Prediction of horizontal stresses in subsiding strata is not possible because of variable and unknown boundary confinement conditions. Virgin horizontal principal stresses in the absence of active or remanent vertical stresses may be estimated by calculation from the following equation:

$$\sigma h = K \sigma v$$

Poisson's Number, K, is found using Poisson's Ratio by:

$$K = \frac{\nu}{1-\nu}$$

Laboratory values of were determined (section 5.3.9) and from these an estimate of Poisson's Ratio for the whole formation can be made. A field value of Poisson's Ratio of

0.3 to 0.4 is assumed for the jointed Waterways Formation. Normal horizontal stress would therefore be from 0.43 to 0.67 times vertical stress.

There is the possibility of remanent excess horizontal stress in the Waterways Formation resulting from one or more of the following:

1. Previous rock overburden. Sproule (1951) has estimated that 900 metres of sediments were eroded since the Upper Cretaceous.
2. Glacial loading. This was much more recent. Maximum ice thickness was as much as 3,000 metres.
3. Horizontal tectonic stresses active during the Laramide Orogeny (50 to 60 million years ago). Babcock (1975) suggests that Laramide stresses may have formed one of the two joint systems in the Waterways Formation.

High unconfined stress tends to dissipate over long periods of time by relaxation but large horizontal stresses are, nevertheless, often measured in near-surface strata, most characteristically in continental shield tectonic settings and in folded mountain belts. Therefore it is unlikely that high horizontal virgin stresses exist in the Waterways Formation. Cicumstantial evidence supporting this view is the fact that the exposed Waterways Formation strata forming the floor of the Suncor open-pit mine have not buckled or heaved. However, this does not eliminate conclusively the possibility of high horizontal stress in Waterways Formation strata distant from valleys (the Suncor mine is adjacent to the Athabasca River valley) or more deeply buried.

If it is assumed that Laramide tectonic stresses are acting in the Waterways Formation, then the maximum principal horizontal stress will be oriented northeast-southwest (parallel to direction of shortening of the Rocky Mountains) and the minimum principal stress northwest-southeast. If magnitudes of the maximum and minimum principal stresses were greatly different, then roof stability may be improved by alignment of openings parallel to the direction of maximum horizontal stress to prevent buckling failure, or perpendicular in order to knit together a loose, jointed roof.

8.3 Rock Mechanics Classification

A number of investigators have related rock behavior in underground excavations to combined properties of the intact rock, characteristics of discontinuities, in-situ stress and groundwater conditions by means of rock classification. This section considers the rock mechanics classification systems of Barton, Bieniawski and Laubscher and using data obtained in this study classifies the following groups of Waterways Formation rocks:

1. Massive Limestone
2. Nodular Limestone
3. Shaly Limestone.

The classification system developed by Barton, Lien and Lunde (1975) is most applicable to rock tunnels and large permanent mine openings, while the other two systems are mining oriented. Each of the systems attempts to quantify rock-mass characteristics as a means to determine an approximate overall rock-mass quality. The quality index can be used variously to estimate unsupported span, support pressures, stand-up time or support requirements. Barton's system determines rock quality, Q, according to the formula:

$$Q = \frac{RQD * Jr * Jw}{Jn * Ja * SRF}$$

The six parameters and their evaluation for Waterways Formation rock are explained and listed in figure 62.

Barton included the following formula as a guide to length of rock bolts used in underground chambers:

Bolt length, L = 2 + 0.15B/ESR

where B = span of opening in metres

and EST = excavation support ratio (classed by Barton as 1.6 for permanent mine openings).

For a span of 6 metres, suggested bolt length L = 2.86 metres.

The two classification systems of Bieniawski and Laubscher are shown in figures 63 and 64. Bieniawski's system leads to estimates of active unsupported spans of 4 metres, 4 metres and 3 metres, for the Massive, Nodular and Shaly lithologies. Barton's system suggests that rock qualities are poorer although estimates of unsupported span are greater (6.5 m, 5.9m and 4.5 m). Bieniawski provides for estimates of stand-up time of the maximum self-supporting span which, for the Waterways Formation, appear short (six months, six months and one week). Barton's system provides charts for determining roof and wall support pressures (figure 62) and also recommends the type of support in each rock type, for openings that are greater than the maximum unsupported span. Recommended support is rock bolting in the roof at 1-1.5 metre spacing. Support requirements determined from Bieniawski's system are slightly more conservative (bolts at 1-2 metre spacing) while those suggested by Laubscher's system are much less (no support, no support, and bolts patterned at one metre). Figure 65 provides a table comparing the three systems.

The authors of each of these classification systems stress that the quality indices are approximations and that systems must be updated by new information, monitoring data or practical experience. Recommendations concerning support are generalizations only. Two general, critical points must be made concerning support and suggested opening use. The stand-up time and support requirements depend on span of opening and the intended use of the opening. Stand-up time can not be designed; it is found by experience. Support requirements are influenced by excavation method and the care exercised while excavating. RQD and rock quality determined from blasted faces or outcrops may be lower than qualities determined from drill core.

There are other factors which limit the usefulness of rock classification of the Waterways Formation. The stress reduction factor of Barton depends on in-situ stress which is not as yet determined. Also undetermined by this preliminary study are the in-situ joint separation (Bieniawski's system), water conditions at specific sites, and the favorableness of discontinuity orientations (which will depend on orientations chosen for openings). Weathering or alteration of joints at depth and the number of discontinuity sets at depth can not be conclusively stated (see section 3.4.5 and 8.7). Finally, in the Waterways Formation, lithology thicknesses are mostly less than three metres so that an excavation will be affected by more than one lithology; possibly by several at one location.

8.4 Comparison of Waterways Formation Rocks and Other Limestones Being Mined

Comparison of mining characteristics of different formations can only be done with practical experience. A study of published references was made for this report, but the limited data presented does not allow careful comparison.

Many of the underground limestone mines in the United States appear to operate in very massive and often recrystallized rock, but in the Fort Dodge Limestone Mine there is one level (32 metre depth) in weak, argillaceous limestone having brecciated dolomite layers and partings of shale five cm thick. The average roof span was formerly 17 metres but with experience this was reduced to 15 metres. Random pillars in the open stoping area were 7.5 metres in diameter. In massive, sparry and fossiliferous limestone at this same mine, rooms were planned to average 360 metres long by 15 metres wide, with height eventually going to 25 metres or more. Drill-and-blast advances in headings were 4.5 metres per round.

Block caving of limestone is carried out in the Riverside mine in California, where the limestone is metamorphosed and strong. Bedding planes and sporadic joints are tight and healed. Compressive strength, density and modulus of deformation values are high, but significantly there are enough solution channels and vugs in the upper zone to structurally weaken the rock mass and allow caving. Undercuts to induce caving of blocks sometimes must be as large as 3,200 square metres. No support is needed in either haulageways or in grizzly drifts, because of the high strength of this limestone.

The Texas Quarry underground limestone mine in Maryland is in a massive limestone that has vertical joints and partings along bedding, both at about 1.5 metre intervals. This causes loosening of large blocks in the roof which are able to fall and necessitates careful scaling and periodic inspection of roofs. Spans of rooms are 10 metres and heights are 14 metres. The fractured state of the rock allows a water inflow of 3800 litres per minute.

Mines in karsted limestone may have to grout extensively, to pump very large volumes of water from the mine and to have special emergency procedures in the case of flooding. A zinc mine in Pennsylvania was flooded several times in recent years despite having pumping capacity of 160 million litres per day.

From this brief survey of literature on limestone mines, it is clear that large spans are possible in moderately jointed and bedded limestone and that with minimal support and maintenance, fairly large spans should also be possible in the Waterways Formation.

8.5 Methods of Excavation in the Waterways Formation

Rock excavation in the Formation could be by the drill-and-blast method or by mechanical excavating machines. Excavation by drilling and blasting is a well established method using basic mining techniques and readily replaceable, non-sophisticated machinery. Actual blasting experience in similar rock is the only practical means of anticipating behavior of the Formation during blasting. To this end, the data provided by this report concerning lithology, intact strength and bedding and jointing will assist blasters to predict which drilling patterns, hole spacing and lengths, and types and amounts of charges will be most efficient. Factors to be considered include size, shape and intended use of the opening, the size of muck and mucking machines, the desirability or necessity of immediate installation of support (or of any support at all), and the relative merits of fast and cheap advance versus the drawbacks of shattered, loosened wall and roof rock with overbreak. Drilling and blasting is a versatile method and can be used under most rock conditions and in excavating openings of any desired size or shape.

Mechanical excavation uses large, expensive and specialized equipment to cut, break or rip the rock. Full-face boring machines excavate by advancing a cutting wheel the full size of the tunnel, into the rock face. Partial-face machines advance by ripping the face with movable booms bearing rotating cutters or spiked heads (eg. the Dosco ~~road~~-header). Both of these machines are expensive in capital cost and in down-time. They do enable more careful and precise excavation than blasting and they allow the installation of support closer to the face more quickly. Full-face tunnel boring machines can do a better job of excavating tunnels of limited size (smaller than about 6 m diameter), and can be more efficient and cheaper in long tunnels even in rock as durable as limestone.

The cost and efficiency of tunnel boring machines depends on cutter performance and thus there is a great need to quantify rock properties in relation to cutting machine performance and cutter costs. Ground stress and deformation and movement of joint blocks while excavating and before support installation, must also be assessed.

Cutter performance predictions at one time were based on intact rock compressive strength, but this is not precise enough. McFeat-Smith (1976) proposes a matrix of the most important rock properties:

a) Quartz content/abrasivity - by itself this may be insufficient, as intensity and type of cementation is important. This can be quantified by thin sections and photomicrographs of broken surfaces.

b) Hardness of cement.

c) Grain size of cement

d) Degree of cementation (porosity).

Rock hardness tests such as the National Coal Board's Cone Indenter test can be directly related to cutter performance. The difficulty in the cutting of intact sedimentary rocks increases with the square of the coefficient of plasticity because the cutting action of drag-pick tools such as road-headers has been shown to be mainly an indenting action and much energy can be absorbed by plastic deformation of the rock, (especially evaporites).

The Dosco road-header performance has been correlated well with cone indenter indices and also with the Shore Scleroscope and the Schmidt Hammer. The Shore Scleroscope is preferred and is more extensively used.

Planes of weakness are extemely important in determining the cuttability and also in determining the size of debris and amount of excavation overbreak. An index of the amount and significance of bedding discontinuities can be found measuring seismic velocities parallel and perpendicular to bedding as proposed by McFeat-Smith: $B = \frac{V_{\parallel}-V_{\perp}}{V_{\parallel}} \times 100\%$. The index B correlates well with cutting performance in shaly rocks but not in other rocks. Planes of weakness are important in determining excavating characteristics and efficiencies by boring or by drill-and-blast techniques.

Tests performed by Steinkohlenbergbauverein indicate that neither mineralogy, strength nor abrasivity of the Waterways Formation limestone (one sample of Nodular Limestone) will restrict tunnel boring machines.

8.6 Ground Control for Underground Excavations in the Waterways Formation

8.6.1 General Planning for Excavation

Underground development in the Waterways Formation for exploitation of the Oil Sands could proceed in two ways: underground mining of Oil Sands or mine assisted in-situ bitumen recovery (section 1.2). Both methods would require extensive tunneling and excavation of large openings. Vertical shafts would be needed if the driving of drift entries were not feasible from Waterways Formation outcrops in one of the river valleys. Inclined shafts might be preferred for ore removal in Oil Sand mining where shaft bottom is not more than 300 metres below surface, but driving an inclined shaft may not be possible because of the nature of the ground. Roesner and Poppen (1978) discuss the problems of shaft sinking for purposes of Oil Sand exploitation and conclude that vertical shafts excavated using either ground freezing or boring techniques must be used. The generally highly water bearing and thick glacial till plus some water sands in the Grand Rapids and Clearwater Formations could present quick-sand conditions during shaft sinking. The McMurray Oil Sands may cave during excavation and are considered non-groutable because of their broad grain size distribution. A shaft lining would have to withstand water pressure for the life of the shaft. A shaft to the Waterways Formation would penetrate the following:

1. Unconsolidated overburden - muskeg, glacial deposits, sand
2. La Bich Formation - shale
3. Joli Fou Formation - sandstone with some shale
4. Clearwater Formation - shale, some glauconitic sandstone
5. McMurray Formation Oil Sands - also contains water sands, and shale and silt intercalations
6. Waterways Formation.

The stratigraphic horizon in the Waterways Formation in which mine tunnels and chambers are developed will depend on geographic location and on depth below the Devonian surface (estimated to be from five to twenty five metres minimum). Figure 2 shows the approximate extent of the subcrop of each member of the Waterways Formation.

Drilling chambers necessarily would have to be larger than access roadways or tunnels for either mining or in-situ operations. To allow sufficient room for drilling injection holes and for installation and servicing of holes, drilling chambers should have spans of eight metres or more. Height of roof would not necessarily need to be as great. If steam for in-situ injection is to be generated underground, there could be a need for large access tunnels to provide enough air to, and venting from, each steam generating station. Any extensive development will have to anticipate some support of excavations in all three of the main lithologic types. In the Calumet and Moberly Members, Massive and Nodular Limestones dominate. Shale and Shaly Limestones are most common in the Firebag, Christina and Mildrid Members.

8.6.2 Failure Modes and Ground Control

Ground behavior is influenced by the state of virgin stress, groundwater, characteristics of discontinuities, intact rock strength, method of excavation, and methods of ground control. Those conditions hindering activity in the openings, which may involve the floor, walls or roof, are considered failures.

The three lithological groups of Waterways Formation rocks will likely be subject to different failure modes. Massive Limestone has high intact strength and will fail only by movement involving discontinuites. Bedding and two near-vertical joint sets (plus numerous random joints) must be anticipated at all localities. This will result in blocky ground with some blocks liable to gravity fall, although openings with spans up to five metres should be largely self-supporting. Block falls from the roof will be more common where jointing is intense and where spans are greater than five metres. Rock falls in closely jointed rock would occur in stages of gradual loosening with falls of layers about 0.3 to 0.5 metres thick, until a stable arch forms, perhaps 1.5 to 2.0 metres above the crown. A similar amount of rock would be involved in roof falls in ground with widely spaced joints, although the material would likely come down in one single fall.

Low-clay Nodular Limestone has high cohesion and would fail by block movement along vertical joints, in a similar manner to Massive Limestone. High-clay Nodular Limestone is rubbly weathering and has low cohesion and would ravel from the walls or roof. Its self supporting ability would be low for openings wider than about three metres.

Shaly Limestone and Shale would fail by gravity falls of tabular pieces defined by jointing and bedding surfaces. Slaking of intercalated bands of shale would assist this process. Shaly rocks would not form large spans without support. Tabular roof or floor layers may fail by buckling or in shear if high horizontal stress exists. Shale walls or floors could swell and where assisted by vertical rock loads, could squeeze or heave into the opening. A shale or shaly floor with water could have very poor trafficability.

8.6.3 Support Measures

Two approaches to control or prevention of failures are passive control and active control. Passive control in the Waterways Formation would involve selection of the most stable lithologic horizons and alignment, both laterally and vertically, of openings. Roofs of openings should preferably be formed of thick layers of Massive Crystalline Limestone or the more cohesive of the Nodular Limestones. The latter may be the least intensely jointed rock type. Massive Limestone would form the most durable floors but acceptable floors could be formed in Shaly or Nodular Limestones. Experience during excavation with floor durability and stability will enable practical choice of floor. For ease of excavation, openings could be placed in weak Nodular or Shaly rocks.

Alignment of openings may prove to be beneficial where some joint sets are absent or less well developed. Babcock (1975) suggests, as does this study, that each outcrop tends to have only one joint system (two sets) developed. Tunneling in ground having only two major vertical joint sets would advance most favorably in a direction that bisects the greater of the two angles between the sets. If high horizontal stresses exist, then alignment of an opening parallel to minimum horizontal stress could assist in roof control. Passive ground control could be assisted by limiting the span of openings or of intersections where possible, by excavating the roof in an arch form and by excercising care in the selection and execution of excavation methods.

A high degree of active support will be needed in bad ground or in roadways or openings that have a designed life of more than one year. Guidelines determined from rock classification (section 8.3) suggest that patterned rock bolting would be sufficient support for large openings in any of the Waterways Formation lithologies. Rock bolts can be used to anchor loose jointed roof layers in platy or massive roofs. Bolted mesh may be necessary where small platy pieces continually loosen and fall. It would be best, but not mandatory, to anchor bolts to Massive Limestone layers.

The purpose of rock bolts in these openings would be:

a) to prevent sloughing of small platy pieces of rock from the roof (perhaps with the aid of steel mesh), and

b) to prevent the general loosening of a jointed roof mass and so to prevent loss of apparent cohesion (and perhaps loss of real cohesion across rock bridges or where there is cement infilling in joints) and thus prevent the loss of its self-supporting capabilities.

Therefore end-anchored and tensioned mechanical bolts would be desirable to provide a moderately stiff support system with little initial deformation.

The bolt length can be estimated from Barton's formula (based on size of opening; see section 8.3) or it could be chosen after exploration yielded information on thickness of weak layers and depth beyond opening wall to solid layers. Bolt spacing should ideally be chosen so as to provide a large, uniform zone of compression in the surrounding rock (Lang, 1961). Lang suggests that bolt length:spacing be 2:1. The spacing would thus depend on bolt length (or vice versa) and also on tensioning pressure.

In areas of weak and rubbly Nodular Limestone, shotcrete may be needed to maintain roof and wall stability. If ground stresses become great enough to cause squeezing of shales, steel arch supports could be used.

Groundwater would be detrimental to trafficability on shale floors and it would promote slaking of Shales, Shaly Limestone, and to a lesser extent of high-clay Nodular Limestone.

8.6.4 Strength of Pillars

Pillars in the Waterways Formation will not exist as such because the size and spacing of anticipated openings will not result in pillars (removal of large amounts of limestone as ore is unlikely). In any case, intact rock strength is high and virgin earth stresses in relation to rock strength are low. Consideration of pillar stability may be necessary where it is desirable to locate double or triple entries (with cross-cuts) as close together as possible.

Pillar stability in general must consider:

1) discontinuity features
2) intact strength
3) effects of weathering and water and long term strength.

As well, behavior of pillars should be monitored to obtain a reference file of information form which to build working models of pillar behavior.

Discontinuities in the Waterways Formation include vertical to near vertical jointing and near horizontal bedding. The discontinuity orientations are favorable for pillar stability. The spacing of joints and bedding varies from very close to blocky. Predictions of strength of pillars formed of many small cubes have been made by Goldstein et al (1966), John (1969), and others. In the strong lithologies of the Formation, intact strength is very high and the reduction of pillar strength resulting from vertical and horizontal discontinuities is not seen as significant.

In the Nodular and Shaly rocks, intact strength is low to medium and jointing would cause further strength reductions. Jointing in the weak rocks appears highly irregular in spacing, orientation and continuity. Pillar strength can be estimated by using general pillar strength formulae (Hedley and Grant, 1972) which utilize pillar dimensions and the strength of laboratory rock cubes. These pillar formulae are based on the relationship of decreasing strength with increasing size of rock specimen (the scale effect). Pillar strength estimations can be improved by assessing the impact of local geological conditions (ie. minor or major discontinuities, thickness of roof layers, etc).

Effects of weathering on pillar strength are not predictable. Weathering was shown to greatly reduce slake durability indices and point load strength (section 5.3) and reductions of similar amounts are likely for compressive strength. Water has been shown to reduce tensile strength (section 5.3) and, although data from this study are inconclusive, compressive strength is also reduced by water saturation. The combined effects of weathering and water would be most serious for the weaker rocks. Also to be considered is the fact that long term rock strength is approximately 30-40% lower than short term, laboratory determined strength (Heuze, 1978).

8.7 Areas for Further Study

8.7.1 Determination of Rock Property Variation

Properties of the rock mass in the Waterways Formation have been found to vary greatly because of lithologic variation between layers and variation of jointing intensity. Chapters two and three have been adressed to these factors. There are, in addition, other factors which cause important inhomogeneities in the Formation and which can be assessed only by extensive field investigations. Foremost are:

1) Solution collapse features
2) Weathering and karst erosion close to the Devonian surface.

Depositional variation laterally has not been found to be significant.

The presence of solution collapse features appears possible at any location in the formation, as geological evidence indicates that evaporite beds at one time underlay the entire region. Evidence suggests that collapse features may be more common to the east of the Athabasca River (Gorrel, 1976). Subsidence, with such associated effects as undulating bedding, loosening of joint blocks, and new fracturing, appears to affect the Formation at all locations in the region. Data on joint occurrence do not indicate regional variation in joint intensity and it appears unlikely that occurrence and severity of subsidence could be detected by joint studies.

The location, magnitude and frequency of occurrence of collapse structures, on the other hand, although not predictable from information presently available, may be relatable to some surface expression ascertainable with the aid of air photographs. Babcock and Sheldon (1976) stated that solution collapse features in the Prairie Evaporite Formation 200 kilometres north of Fort McMurray are structurally controlled and occur along fault lines. They noted an arcuate alignment of possible sinkhole ponds developed on Waterways Formation strata near Maclelland Lake, 95 kilometres north of Fort McMurray. Demarcation of linear zones of collapsed ground could aid in placement of tunnels in safer ground. Hackbarth (1977) believes that the Athabasca River in part delineates a fault zone along which more rapid salt solution has occurred. The terrain near the valley of the Athabasca River north of Fort McMurray does contain numerous collapse structures with considerable strata disruption which, because they extend 50 metres or more below the Oil Sands contact, could have serious consequences for underground mine development.

Effects of weathering and karst erosion on the Waterways Formation are only poorly known (see section 5.4). In outcrop, some Massive Crystalline Limestones are virtually unweathered except for a few mm on the outside of each jointed block. Rock having high clay content is always highly weathered in outcrop. In core, slight weathering and bitumen impregnation is noted along joints and fractures up to 30 metres below the weathered Devonian surface (bitumen was not observed along bedding, even where it intersected tarry joints). There is high to extreme weathering of some core intersections of the Devonian surface resulting in soft, powdery, and easily broken limestone for 0.10 to 0.40 metres below the erosion surface. Weathering effects appear to diminish rapidly below this uppermost zone. Karst erosion of the Devonian surface has been reported (section 6.9). The lateral and vertical extent of this erosional process is not known.

8.7.2 Remote Detection of Geological Contacts

Excavation for mine development in the Waterways Formation could proceed in an orderly fashion if the chosen rock horizon continued laterally at a similar elevation. Tunneling horizontally across dip would encounter beds of different lithologies which might hinder progress of a tunneling machine. However attempts to tunnel across some other types of geological contact could be hazardous and very costly and their detection would be needed to provide adequate time either to prepare for the new conditions or for tunnel rerouting. Possible geological hazards include:

1. Topographic lows on the Devonian surface where very weathered and porous limestone and/or McMurray Formation water sands are at a lower elevation than anticipated.

2. Brecciated, unstable and water bearing collapse zones in the Waterways Formation.
3. Water filled caverns within the Waterways Formation.
4. Faults (associated with or without collapse structures).

The location and extent of any of these four features along a tunnel route should be detected at an early stage of planning. Remote sensing techniques are applicable to the near-surface and perhaps to a depth of 30 metres (Lamoreaux, 1979). Remote sensing should be the first step in field exploration for any structural anomalies. Techniques include side-looking airborne radar, thermal infrared and reflected infrared and visible electromagnetic radiation in several wavelength regions at once. Information can be applied to mapping alignments of dolines, making an inventory of and monitoring the development of, dolines, and investigating the relationship between dolines, groundwater and fracture traces and lineaments. Remote sensing is able to detect areas of abnormal surface drainage and areas where vegetation differences indicate incipient ground surface collapse (Lamoreaux, 1979), although the near surface location of the groundwater in the Athabasca region would present difficulties.

Initial drilling and geophysical investigation from surface could satisfactorily locate large features such as topographic lows, but smaller structures such as caverns would be detected only with comprehensive and expensive investigation on a scale of tens of metres. A geophysical method such as ground-probing radar or acoustics would appear to be the most useful. Either acoustics or ground-probing radar could be used from surface, from a tunnel face or from boreholes.

An important class of radar targets is composed of large objects which are wetter than surrounding material, such as water-filled voids. According to Cook (1974), varying the frequency of ground-probing radar allows detection of discontinuities ranging from two cm to 40 metres in size. Cook's experiments in underground mines succeeded in locating adjacent mine openings through at least 9 to 18 metres of rock. But he considered that equipment and techniques for each different type of field problem (in 1974) required experimentation by research scientists.

Price (1974) reported that acoustical holography could produce three-dimensional images of rock structure for a distance ahead of the tunnel face equal to two to three times tunnel diameter. Drilling long horizontal holes ahead of a tunnel is feasible for distances of perhaps 100 metres (figure 66). This would provide geotechnical information important for tunneling, including location of danger zones. The insertion of geophysical probes, for detecting acoustic, seismic or other geophysically generated signals, into these holes would extend the range of detection to include nearby faults, caverns and the Devonian/Oil Sands contact (figure 66).

8.7.3 Field Testing of Rock Mass Features

Virgin stress and groundwater characteristics in the Waterways Formation have an influence on excavation procedure and possible tunnel or shaft linings. Both must be measured by field testing in the Waterways Formation.

Virgin stress determination is primarily concerned with high horizontal stress because vertical stresses can be calculated from depth of overburden. Hydrofracturing or borehole jacking techniques of stress measurement would permit relatively deep measurements of absolute stress (Heuze 1978, Haimson 1977, De La Cruz 1977).

Permeabilities and water pressures in various horizons likely to be encountered during mine development should be measured by piezometers, borehole packer tests and well pump tests. Hydrological information obtained will allow estimation of rates of water inflow to mine openings and determination of water pressures associated with mine-assisted bitumen recovery. These intervals or water bearing zones are:

a) a well jointed Massive Limestone unit of the Waterways Formation

b) a Shaly Limestone unit of the Waterways Formation

c) water sands near the base of the McMurray Formation Oil Sands

d) the zone of weathered strata adjacent to the Devonian/Cretaceous unconformity

e) a Karst collapse chimney in the upper part of the Waterways Formation infilled with argillaceous sands or conglomerates.

Testing [illegible] two units would provide hydrological information [illegible]ound which is assumed to be representat[illegible] of the total length of potential tunnels in the Waterways Formation. The last three points are suggested in order to assess the problems posed by the most likely of the hazardous groundwater conditions.

In summary, further studies of the Waterways Formation should be field studies at a specific site and should be part of a program of exploration and testing of all the rock formations to be involved with underground excavation. Exploration and testing of ground and groundwater conditions can first be conducted from surface and then from underground in conjunction with the drivage of each of the excavations. Tests of virgin rock stress and of groundwater conditions in the Waterways Formation should be part of the initial surface investigation. A program of monitoring all rock mechanic features must be continued for the life of the project.

9. INDUSTRIAL USES OF THE WATERWAYS FORMATION

An industrially advanced economy has hundreds of uses for limestone. Of the limestone mined, more than 90% is used in only a few products or processes such as cement, dimension stone, aggregate stone and lime production.

The economic feasibility of limestone production from the Waterways Formation for any of the listed purposes is not investigated here. Restricted local markets and long transportation distances are negative factors for a limestone industry in the Athabasca Oil Sands region, however the production of limestone as a by-product from an Oil Sand mining venture may some day be an incentive to commercial production. This chapter will detail some of the more important industrial uses of limestone, their quality requirements and possible suitability of the Waterways Formation limestone for these uses.

9.1 Limestone Production

Limestone can be mined either from open-pit or from underground mines. In the United States for example, there are over 100 underground limestone mines, using block-caving or room-and-pillar mining methods. The economics of open-pit limestone mining in Pennsylvania allows the stripping of 18 metres of rock and unconsolidated overburden in order to recover about five metres of limestone.

In the Oil Sands region, limestone could be produced from surface limestone mines, from limestone floors of then-existing open-pit Oil Sands mines, or from underground as waste rock resulting from excavation of bitumen-recovery chambers in the Waterways Formation (or other Upper Devonian limestones).

To obtain high quality limestone from surface operations in the Waterways Formation would require selective recovery of Massive Crystalline layers and rejection of argillaceous limestone. Massive Crystalline layers are seldom thicker than two metres. The desired quality could be attained by selective mining or by selectively screening the crushed rock, because during crushing the weak argillaceous limestone would tend to break apart easily or be ground to a fine size. Argillaceous limestone may be acceptible for some purposes. Selective production of good-quality limestone from mine tunneling operations would likely be impossible due to intimate mixing of different lithologies during the exavation process.

9.2 Uses of Limestone

Each of the uses to which raw limestone is applied has different physical and chemical specifications for the source material. The major uses of limestone are discussed in this section along with brief summaries of product specifications for each use. Before discussing the applicability of the Waterways Formation limestone for industrial use, some initial data on chemical analyses of

Waterways Formation rocks performed by Carrigy (1959), Holter (1973), Hamilton and Mellon (1973) and by this study (1979), are presented in figure 67.

9.2.1 Cement Production

Limestone is the major constituent in cement, which is a complex mixture of calcium, aluminum and iron silicates that is able to hydrate and solidify. Clay or shale is added as a source of alumina, silica and iron, although it may be possible to utilize limestone from the Waterways Formation that contains the correct proportions of these components. Gypsum or anhydrite, which is added to retard the setting time of cement, is obtainable from the Prairie Evaporite Formation in the Oil Sands region.

Limestone for cement should normally contain less than five percent dolomite, although eight percent may be acceptable. The silica and alumina content of limestone is of much less importance, as clay or other material can be added if needed. Sodium, potassium and sulfur are undesirable elements, but in the Waterways Formation, potassium has not been encountered and sodium (halite) occurs only in minute amounts. Sulfur, in the form of iron sulfide minerals, sometimes occurs in significant amounts in the Waterways Formation.

9.2.2 Limestone Aggregate

Limestone has been used as an aggregate in concrete,

concrete building blocks or asphalt, but the abundant supply of glacial debris in Canada generally supercedes the use of limestone for this purpose. Limestone for aggregate must be stong, durable and free of soft lumps or concretions. Limestone can also be used as rip-rap or fill material in roads and other earth constructions, in which case the specifications are not as strict. Figure 68 presents one classification method of limestone for use as an aggregate. The best limestone for these purposes is tough and non-porous, with few clay laminations.

Large blocks of Massive Crystalline Limestone have been used as rip-rap in the Fort McMurray area and in addition some Waterways Formation limestone has been used in local road construction.

9.2.3 Dimension Stone

Limestone used for dimension stone may either be cut to specified sizes from massive blocks or it may be produced in small, irregularly shaped pieces to be used as is. Fractures, mineralization and solution cavities may render limestone unusable as dimension stone. Massive dimension stone must be amenable to quarrying in large blocks that can be extracted, transported and installed economically without breaking. A major problem is splitting along bedding at undesirable intervals.

Jointing and bedding in the Waterways Formation are closely and irregularly spaced and would prevent quarrying of large blocks of dimension stone. But layers of Massive Crystalline Limestone and also of some Shaly Limestone weather to form durable book, brick and block-shaped pieces that are readily usable in construction. The possible low cost production of building stone from outcrops near Fort McMurray along the Athabasca River could generate a market for Waterways Formation limestone which does not now exist.

9.2.4 Production of Lime

Lime is produced by the heating or calcination of limestone or dolomite. Lime has numerous uses in the chemical, metallurgical and construction industries, including use as a flux in the basic-oxygen method of steel manufacturing.

Stone for lime should contain about 98% carbonate, should have a uniform grain size, be hard, and not decrepitate during heating.

Analysis of the Waterways Formation reveals limestone having 97% carbonate and some Biolithic layers may be acceptable for lime making. However these layers would not provide large volumes of limestone and dilution with argillaceous limestone would be difficult to prevent.

9.2.5 Air Quality Control

Concern about sulfur in some industrial processes and atmospheric emission of sulfur dioxide is resulting in the introduction of scrubbing processes requiring limestone. In the production of coke and synthetic crude oil, limestone can be used as a fluxing agent that combines with impurities such as sulfur and prevents their release as gases.

The steel industry uses limestone or lime to scrub stack gases containing sulfur dioxide by two methods:

a) injection of lime or limestone into the furnace to react with sulfur dioxide, or

b) passing the stack gases through a slurry of lime or limestone.

While high calcium limestone is most desirable, a low sulfur content is essential. Continuing research suggests that small grain size and high micron-size porosity limestone is the most efficient.

Sufficiently pure limestone may be uncommon in the Waterways Formation. Clay content is generally a minimum of a few percent and disseminated sulfide minerals are a common occurrence and could prevent its use for lime.

9.2.6 Agricultural Use of Limestone

Crushed limestone can be added to neutralize soil acidity and also to improve other soil characteristics. This is not foreseen as a potential use of the Waterways Formation because of the lack of agriculture in the area.

9.3 Physical Tests to Determine Industrial Use of Limestone.

The determination of limestone suitability for industrial purposes usually consists of chemical analyses only. To determine suitability for aggregate and dimension stone there are a number of physical tests (figure 69) discussed in the following sections.

9.3.1 Tests for Dimension Stone

Dimension stone must be strong and durable. The Compressive Strength and Modulus of Rupture tests are methods of measuring rock strength. The Abrasion Resistance test measures the resistance of limestone to abrasion by foot traffic.

9.3.2 Tests for Aggregate Stone

Aggregate should be strong, hard, non-porous and resistant to crushing. The State of Indiana classifies aggregate stone for different uses (figure 69). There are several tests used to determine the quality of stone for aggregate, among which are:

1) Abrasion. The Los Angeles Abrasion test is most commonly used and provides data useful in predicting how limestone aggregate would endure wheel traffic or how much strength it would impart to concrete.
2) Determination of Fines Content. Excessive fine material in concrete aggregate decreases mortar

strength.

3) Determination of Clay Lumps. Lumps of clay and other soft material are low in strength and can change volume when wet, frozen or when subjected to loads. There shoud be few soft lumps.

4) Scratch Hardness. Classifies limestone as hard or soft. Hard limestone is desirable.

5) Sieve Analysis. Determines the particle size distribution of fine and coarsely crushed stone aggregate.

6) Soundness (Sulfate Soundness and Freeze-Thaw tests). The Sulfate Soundness test measures the resistance to a solution of sodium or magnesium sulfate. The Freeze-Thaw test measures resistance to freezing and is more important in cold climates. Resistance is influenced by water absorbtion ability.

7) Specific Gravity and Absorbtion Tests. These measure the amount of void space and enable proper mixture of concrete aggregates and correct proportioning of water for concrete.

9.4 Summary of Industrial Uses of Waterways Limestone

A limestone industry in the Oil Sands region would have to overcome the two disabilities of lack of , or restricted size of markets, and large transportation costs.

Waterways Formation limestone could be used for cement and lime production, for fluxing and desulfurization of crude oils and synthetic oils, and for aggregate and dimension stone. Limestone has been used in road construction near Fort McMurray and this use will likely continue. Careful monitoring of raw limestone would be necessary to maintain product quality for all of the listed uses, because of the presence of variable amounts of clay, magnesia and sulfide minerals.

Massive, Nodular or Shaly Limestone or mixtures should be suitable for cement. Contents of magnesia or sulfide minerals may occasionally be greater than desired. Lime could be produced from some layers of Biolithic Limestone where calcite content is as high as 98% and where sufficient tonnages are accessible. Limestone for fluxing may be obtained from pure layers of Biolithic Limestone.

The best limestone for aggregate would come from the very durable layers of Massive Limestone. Massive Crystalline Limestone has not been subjected to some of these quality tests but other measured qualities suggest that it would serve as top quality aggregate stone. Dimension stone could be obtained from platy to blocky layers of Shaly Limestone or Massive Crystalline Limestone.

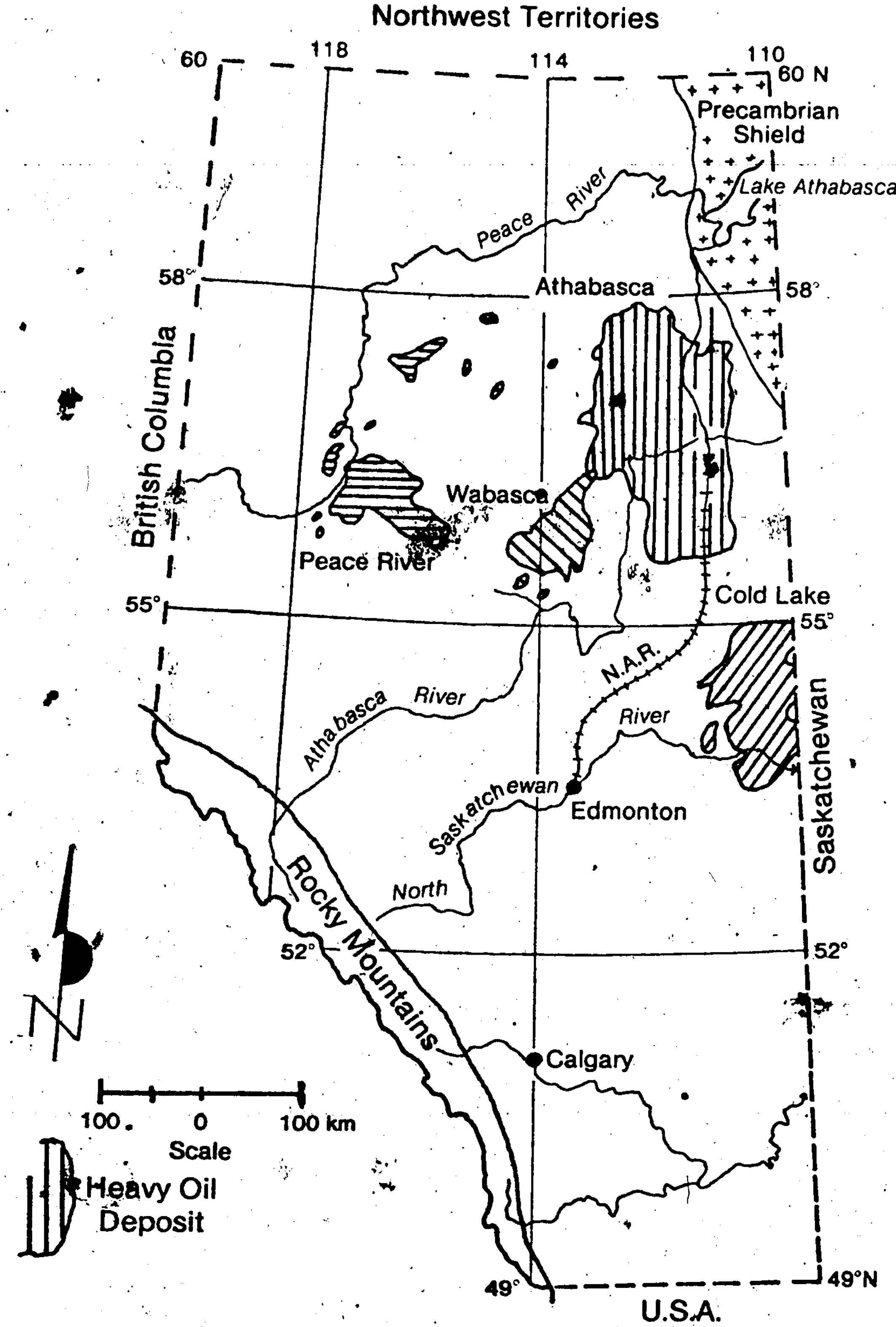


Figure 1. Location Map of Heavy Oil Deposits of Alberta Showing the Athabasca Oil Sands.

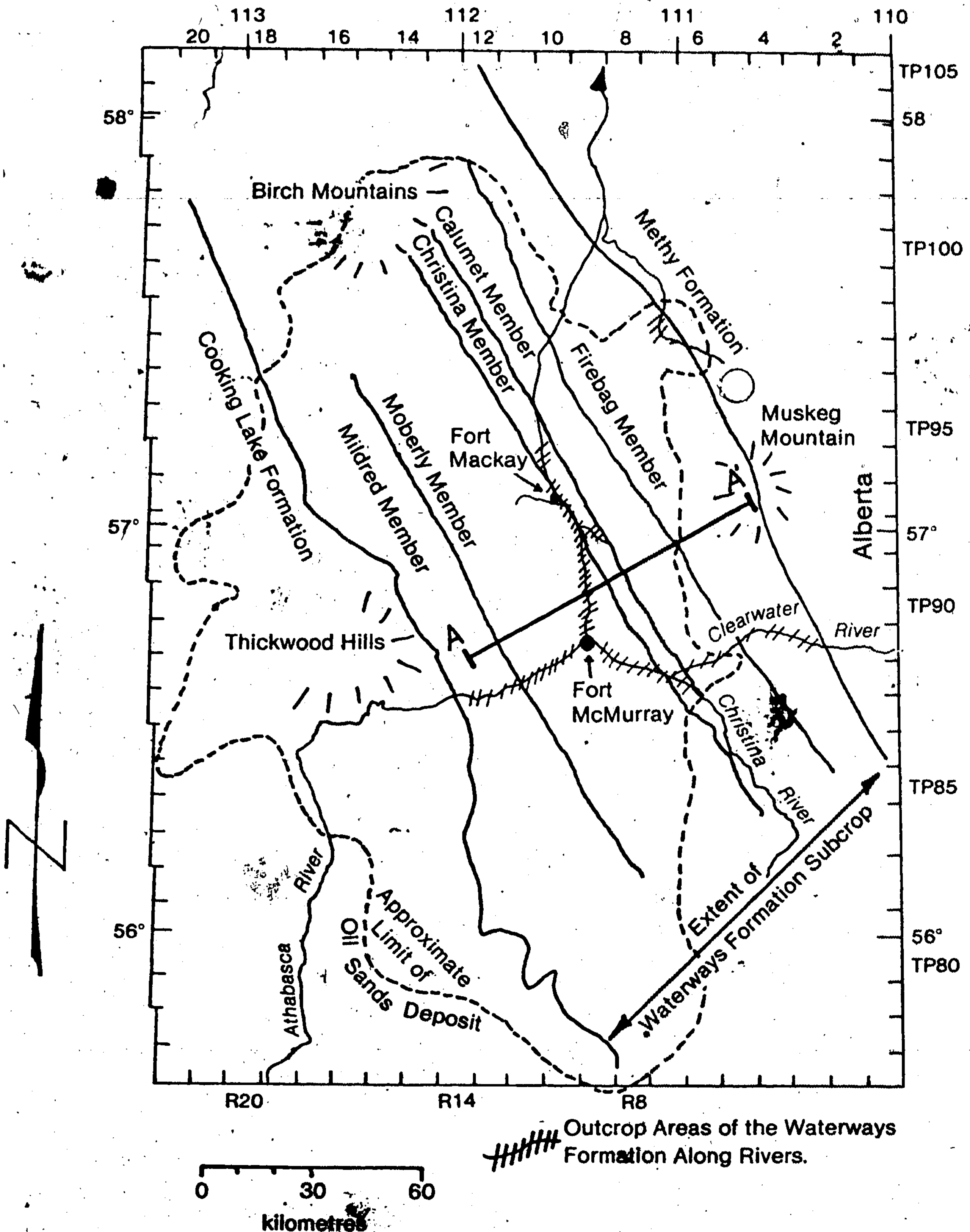


Figure 2. Location Map Showing Areas of Discontinuous Outcrop of the Waterways Formation and the Subcrop Extent in Relation to the Athabasca Oil Sands.

PLEISTOCENE and RECENT	Glacial till; silts, sands and gravels.
unconformity	
CRETACEOUS	
La Bich Formation	Shale
Pelican Formation	Sandstone
Joli Fou Formation	Shale
Grand Rapids Formation	Lithic sand and sandstone
Clearwater Formation (with basal Wabiskaw Member)	Shale, siltstone (glauconitic sandstone)
McMurray Formation	Quartz sand with bitumen; silty and clayey lenses
unconformity	
UPPER DEVONIAN	
Woodbend Group (with basal Cooking Lake Formation)	Reef limestone, shale, and argillaceous limestone
Waterways Formation	Argillaceous lst, lst and shale
Slave Point Formation	Limestone and dolomite
MIDDLE DEVONIAN	
Prairie Evaporite Fm.	Anhydrite, halite, gypsum and dolomite
Methy Formation	Reefal dolomite
Maclean River Formation	Dolomite, claystone and evaporites
La Loche Formation	Basal "Granite Wash" sandstone
erosional unconformity	
PRECAMBRIAN	Metasedimentary rocks and granite

Figure 3a. General Stratigraphy of the Oil Sands Region (modified after Carrigy, 1973).

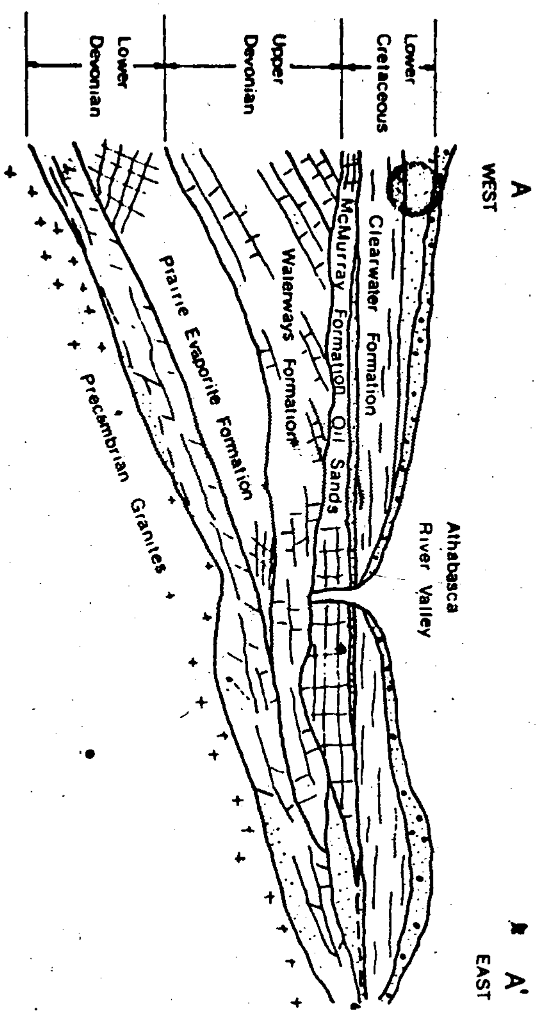
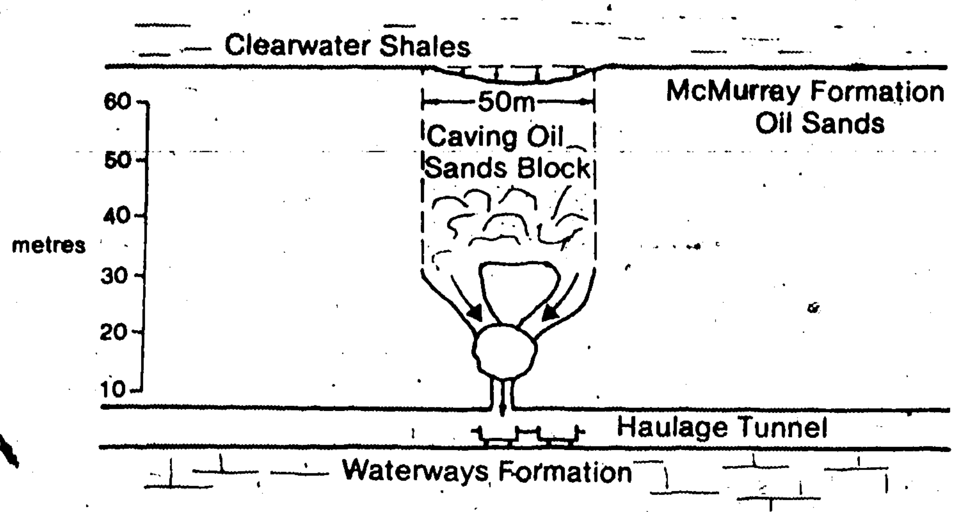


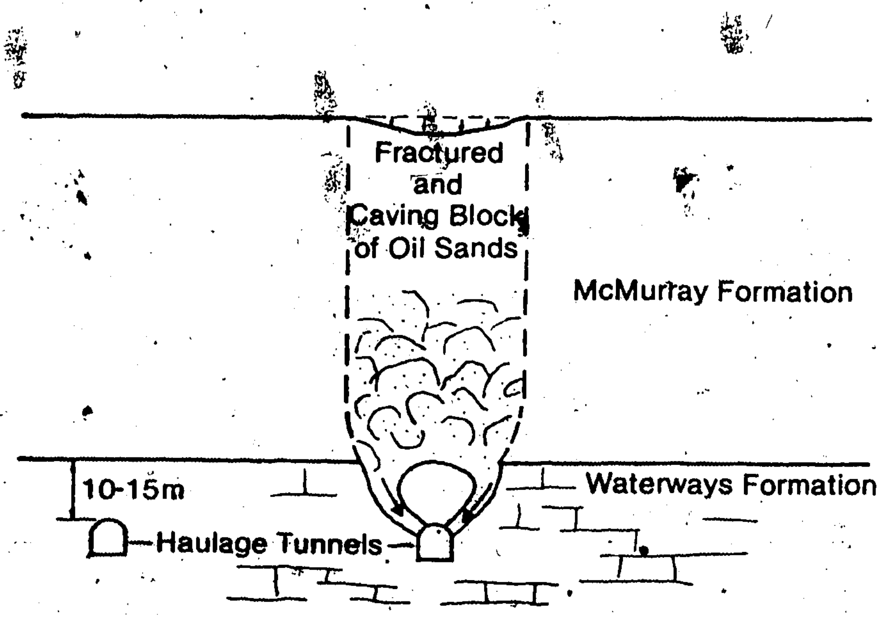
Figure 3. General Stratigraphy of the Oil Sands Region With Cross Section.

RECOVERY METHOD	ROLE OF WATERWAYS FORMATION
1. Surface Mining	Floor of Mining Operation
2. Underground mining within the McMurray Formation	Floor of Underground Mine
3. Underground mining operated from Waterways Formation	Location of development works
4. Block caving of McMurray Formation-combined with MAISP from Waterways Fm.	Mine development plus tunnels and chambers for MAISP
5. Surface based in-situ	Lower limit of ore
6. MAISP From Clearwater Fm.	Lower limit of ore
7. MAISP from McMurray Fm.	Lower limit of ore
8. MAISP from Waterwys Fm.	Tunnels and chambers for in-situ injection and recovery.

Figure 4. Table of Proposed Bitumen Recovery Methods and their use of the Waterways Formation.



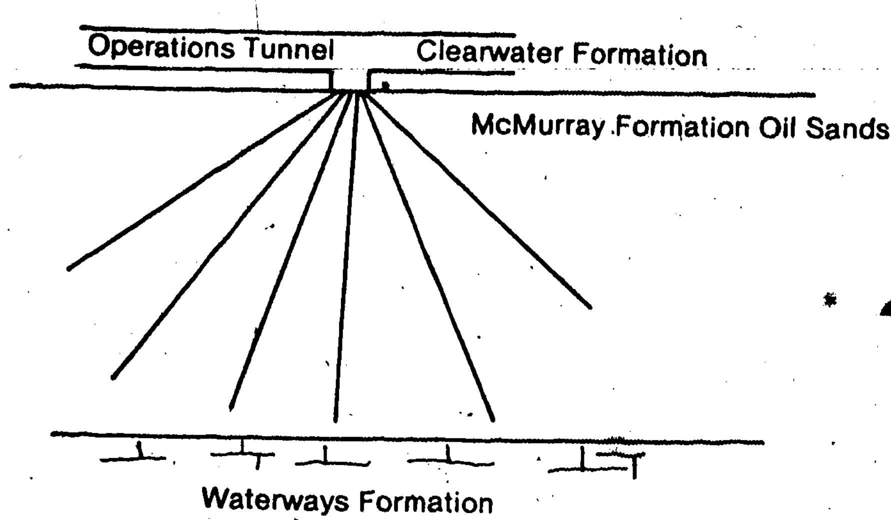
a) Block Caving Operation Within the McMurray Formation



b) Block Caving Operated From the Waterways Formation

Figure 5 a,b. Diagrams of Proposed Bitumen Recovery Methods.

c) MAISP From The Clearwater Formation



d) MAISP From The Waterways Formation

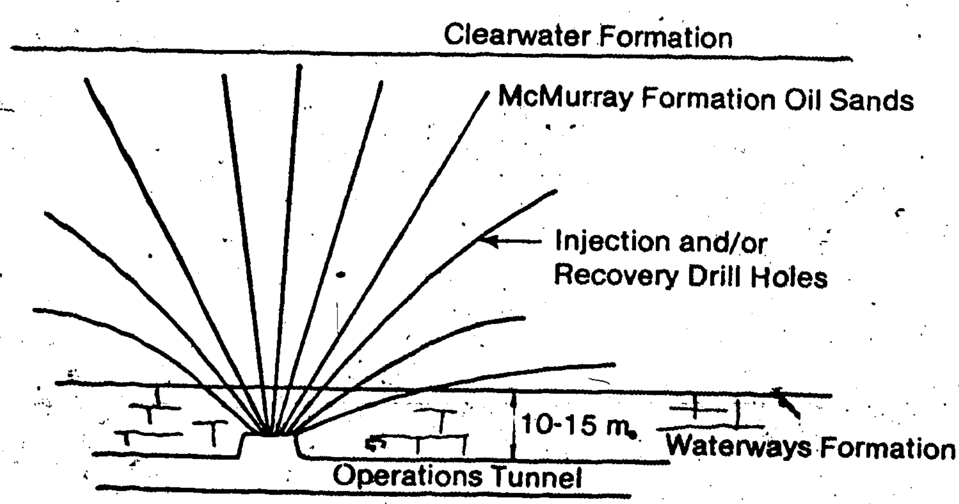


Figure 5 c, d. Diagrams of Proposed Bitumen Recovery Methods

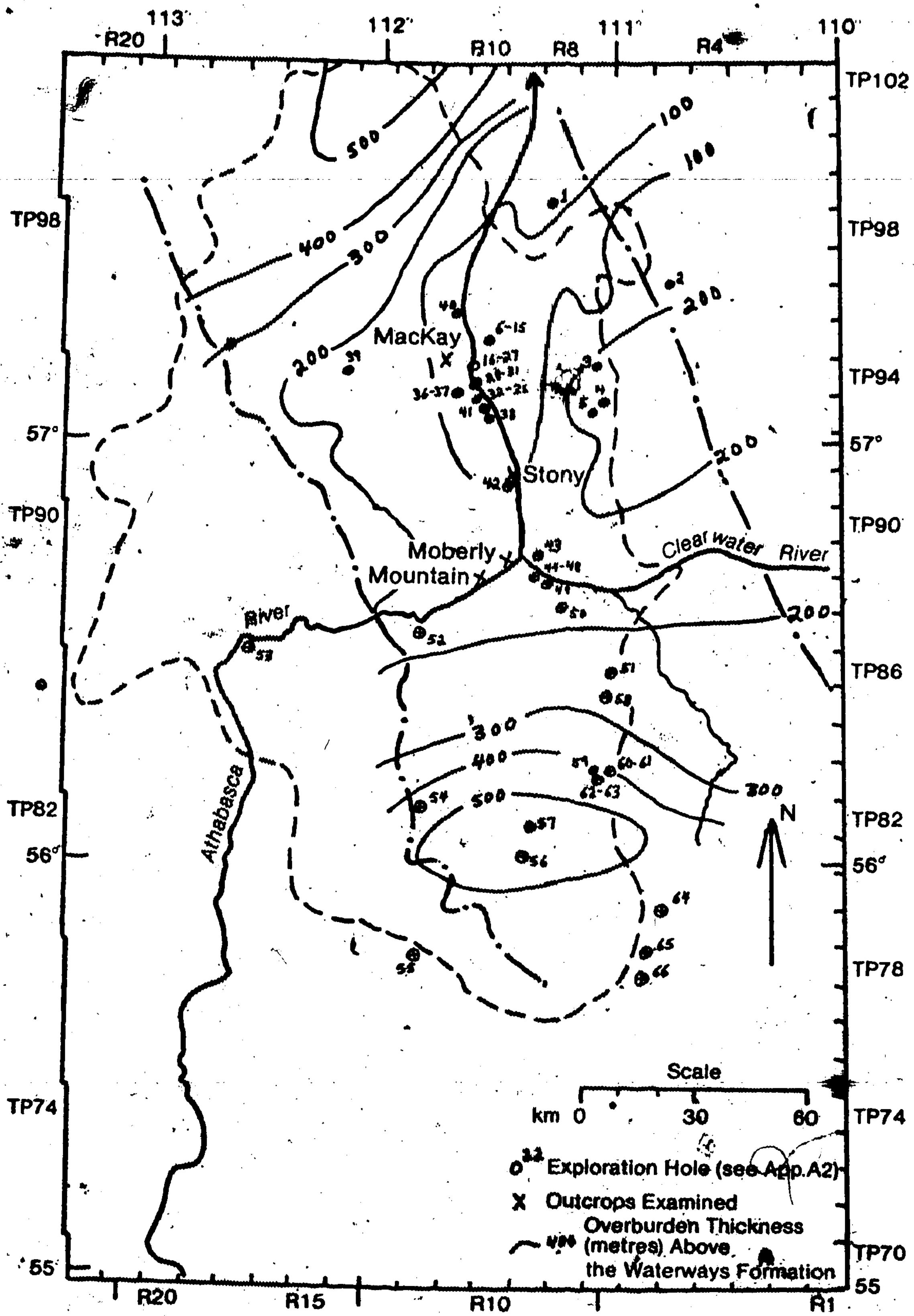
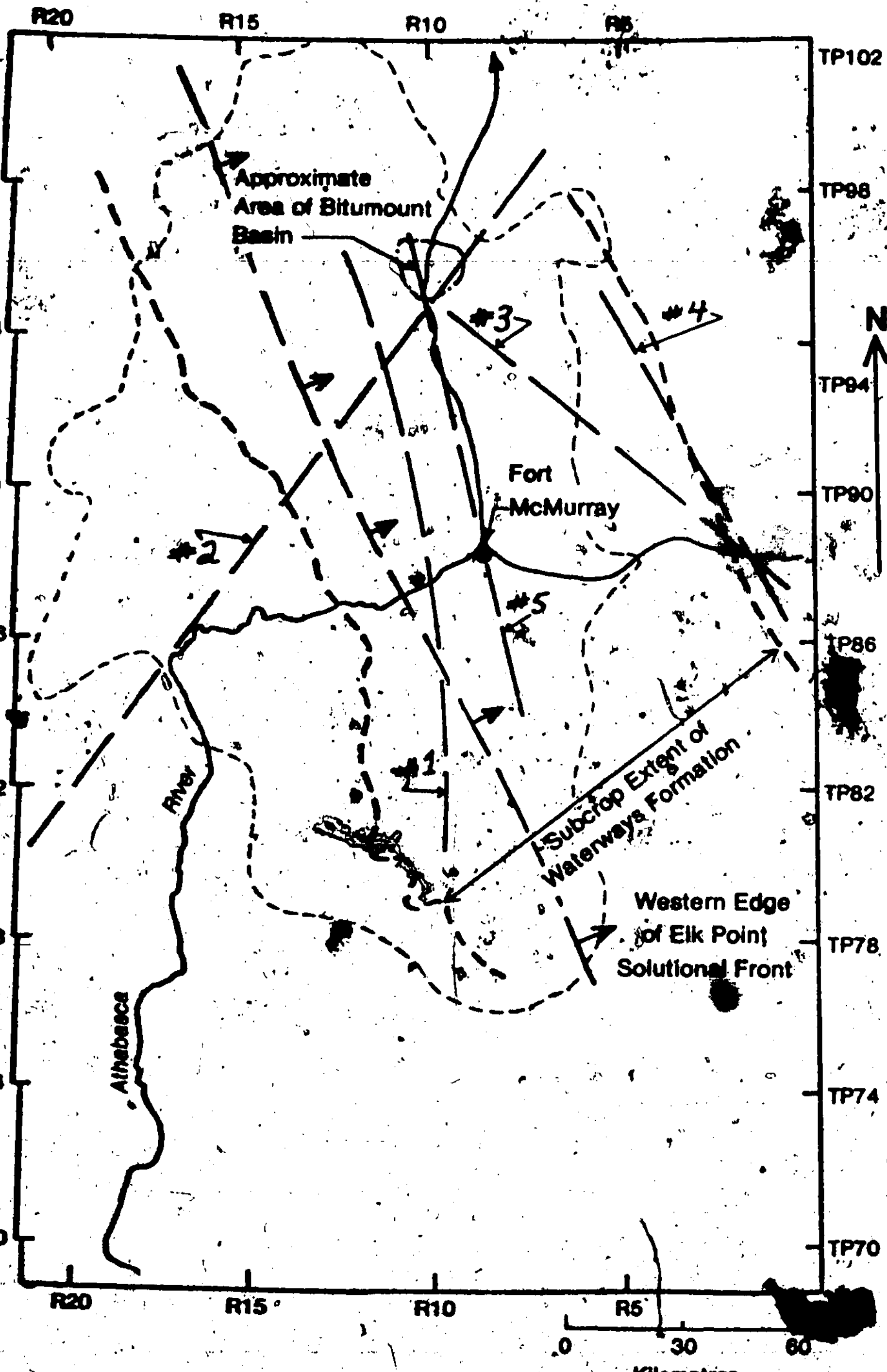


Figure 6. Map of Oil Sands Region With Waterways Formation Coreholes and Overburden Thickness.

Woodbend Group	
Cooking Lake Formation	Pale brown, fine-grained calcarinitic limestone, partly dolomitic and argillaceous. 44 metres.
conformable	
Mildrid Member	Greenish-grey calcareous shale and argillaceous limestone; some brownish clastic limestone. 42 metres.
Moberly Member	Alternating sequence of light greenish, rubbly limestone and shale, thinly interbedded with variable clay content. Also durable beds of brownish aphanitic fragmental limestone. More shaly to top and to north. 61 metres.
Christina	Mainly greenish-grey shale, grey argill. limestone, brownish aphanitic limestone and fragmental limestone. Some sandstone and sandy limestone. 27 metres
Calumet Member	Mainly clastic limestone with variable clay content; some greenish nodular calcareous shale and minor non-calcareous shale. 31 metres.
Firebag Member	Greenish calcareous shale with thin units of limestone, argillaceous lst and non-calcareous shale. 53 metres.
paraconformable	
Slave Point Formation	Limestone, silty limestone, siltstone and minor dolomitic lst. 5 metres.

(Mildrid, Moberly, Christina, Calumet and Firebag Members: WATERWAYS FORMATION)

Figure 7. Stratigraphic Section of the Waterways Formation.



#1, see text, page 14

Figure 8. Map of Oil Sands Region Showing Interpreted Structure and Faults.

Performed By/For:	Purpose/year	Location	Comments
Dames and Moore for Suncor	Study of bedrock foundation for Oil Sands plant 1962	Suncor plant site	Bearing capacity found to be sufficient
Thurber Consultants for Alberta [illegible] Transport	Study of bedrock foundations for bridge crossings 1978-79.	Ft. McMurray, 3 sites along river south of Fort Mackay	Various lab test performed (see Fig. 10b)
Hardy and Associates for Petro Canada MAISP project.	Study geology and characteristics for large pressurized boreholes. 1978-79.	Waterways escarpment along Athabasca River	Various lab tests (see Fig. 10b)
Babcock with Alberta Research Council	Study of orientation of joints and lineaments 1974-75	Various outcrops along Athabasca River and tributaries	observations on regional joint occurrence and alignments
EBA Consultants for Shell Oil	Suitability of rock for industrial use 1964.	Lease #13 northeast of Fort Mackay	suitable for cement making
Golder Associates for Canmet	mining geotecinical evaluation 1979	general	rock mechanics and mining investigation

Figure 9. Previous Geotechnical Investigations of the Waterways Formation.

HARDY AND ASSOCIATES

1. Point Load Indices

Rock Type	Orientation to Bedding	Is50 (MPa) Average	Is50 (MPa) Range	No. of Tests	Strength Class
limestone	parallel	0.88	0-3.90	13	medium
argillaceous limestone	parallel	0.31	0.03-0.31	6	medium
shale	parallel	0.57	0.02-1.12	2	medium

2. Direct Shear

Rock Type	Ø/Ores	Cohesion (KPa)
limestone - intact	[illegible]	150
limestone - smooth, planar joint	[illegible]	0
limestone - rough, planar joint	43	150
limestone - weathered	30	0

THURBER CONSULTANTS

3. Uniaxial Compression

Rock Type	cave (MPa)	No of Tests	Ave. Specific Gravity	Natural Moisture Content
limestone	64.9	7	2.62	
limestone-fractured	17.2	3	2.53	
shale	1.1	3	2.39	5.7%

4. Swelling Tests

Rock Type	% Clay	Silt Sand	% of Total Rock Illite	Kaolin	Vermic	Swelling Constant Volume	Pressure KPa Rebound
Shale	27.5	72.5	20	5.5	1.5	18.0	22.0
Shale	9.0	91	7.7	1.3	0	2.0	
Shale	20.0	80	15.0	4.0	1.0	1.5	2.0

Figure 10. Results of Previous Geotechnical Tests on Waterways Formation Rocks.

Depth (m) / sample no.	Rock Type	Pictorial	% RQD / mm. ave length RQD	Slake Durability (20 40 60 80 100)	Field Strength (vw w m s vs)	Drilling Rate mm/min (25 50 75 100)	Hand Breakability Index (Ave. length of frag. mm)	Hardness (5 4 3 2)
(1)	[illegible] LST.		NA				NA	
	NODULAR LST.		NA				24 mm	
(4)	FOSSILIF. LST.		NA (COMPLETE)				STRONG	
	NODULAR LST (HIGH-MED. CLAY)		NA				966 mm	
(7)							37 mm	
(8)	FOSSILIF. LST		NA					
(10)	(MED. CLAY) NODULAR LST		NA				182 mm	
	SHALEY LST.		NA				45 mm	
(12) 2	NODULAR LST		NA			?	46 mm	
(14)	BANDED SHALEY LST.		97.6% 195 mm	70.5% … 92%			16 mm	
4 (21) (25)	BIOLITHITE		NA				STRONG	
6, 8, 10	V. HIGH CLAY – NODULAR LIMESTONE; LOW CLAY; LOW CLAY; NODULAR LIMESTONE; V. LOW CLAY		98.6% 392 mm (MID-SECTION IS FIRM – SEE HAND BREAK. INDEX)	96%		?	BREAKS EASILY = 20 mm; QUITE FIRM & COHESIVE = 110 mm; 417 mm (26 mm)	
(46) 12	BANDED SHALEY LST.		100% 610 mm	(THIS INTERVAL NOT TESTED)			120 mm	
(48) 14	LOW CLAY – NODULAR LIMESTONE; MED-CLAY; HIGH CLAY		100% 478 mm	(THIS INTERVAL NOT TESTED)			NOT HAND BREAKABLE 508 mm; 114 mm	
(53)	BANDED		96%				BREAKS EASILY	

Field Strength (VW W M S VS)	Drilling Rate mm/min. (25 50 75 100)	Hand Breakable Index Ave. length of frag. mm	Hardness (5 4 3 2 1)	Bedding Joint	Lithology Description
		NR		LAMINATED	FINELY LAMINATED, V. WEATH
		24 mm		V. [illegible] JOINT AT BASE →	LT. COLORED LAM. & DETRITAL ZONES IN [illegible] LST.
		STRONG		TARRY [illegible]	[illegible] FOSSIL. FINE CRYSTAL MATRIX
		66 mm		STARTS WITH FRAC. IN BEDDING ZONES DIP = 85°	MED. XTAL. SPARRY
		57 mm		[illegible]	V. FOSSIL. IN A WELL XTAL. MATRIX
		182 mm		[illegible] BUT ALL IN ONE	ROUNDED NODS. SET IN A DETRITAL & FRAG. MUD MATRIX.
		45 mm		MOST SMOOTH BED. TALCY CLAY [illegible]	BREAKS EASILY ALONG SMOOTH BEDDING, V. CALC., DISS. [illegible] IN FINE XTAL. LST.
	?	[illegible]		IRREG. BED.	IRREG. MATRIX AREAS OF HIGH CLAY
		16mm		4-8 mm BANDS, QUITE SMOOTH, REGULAR. SOME SLIGHT WAVY BANDS SL. GREASY	BANDS 4-8 mm OF GREEN CAL. CLAY & GLASSY CRYSTALLINE GREENISH LST. FEW PYRITE NODS (1-8 mm). BANDS ARE DIFF. IN HARD, COLOR, BANDING IS REG, CONTIN., SO THAT CORE IS BEG'LY WK. AT ALL ARGILL. BANDS BECOMING LESS & THINNER ARG. BANDS → FIRMER & HARDER.
		STRONG		LAM. AT [illegible]	SHALEY-LENSEY AT TOP & BASE [illegible] XTAL. DETRIT. FOSSIL. LST.
	?	BREAKS EASILY = 20mm QUITE FIRM & COHESIVE. = 110 mm 417 mm		MASSIVE. BREAKS VERY IRREG. BETWEEN NODULES A FEW TARRY FRACS. V. DISCONT. LAYER OF COQUINA NODS. SLIGHTLY ALLIGNED HORIZ. @ 9.3 m. - REAL BRITTLE BRECCIA ALONG A. VERT. FLOW PATH	CLAYEY NOD. & SOME IRREG. BANDED PLACES. NODS ARE GLASSY XTALL, PARTLY WEATH. STILL HARD, WHILE CLAY CRUMBLES AWAY FROM [illegible]. MATRIX HAS NO APPARENT RELATION TO HORIZONTAL. APH. & CONCOIDAL, NODS = ~85% MATRIX = 15%, NODS BECOMING MORE ROUNDED. @ 6.7 m IS A SMALL SPARRY & TARRY VUG. @ 7.3 m A LAYER OF SEVERAL BRACHS OF ARAGONITE. TOUGH FOSSIL ZONE. BELOW IS V. TOUGH, BRITTLE CONCOIDAL APHANITIC LIMESTONE. A FEW TARRY FRACS. WHICH ARE FRESH & BLACK OR BROWN WAVY ARGIL. ZONES MORE LENSY & HORIZ. NODS ARE GREY - LIGHT TO MEDIUM. MATRIX IS BROWNISH FINE XTAL - APH.
		(35 mm) 120 mm		A SET OF SMALL VERT. FRACS. (NOT ORTHOG.)	MATRIX CHANGES INTO WEAKER, LENTICULAR, MORE EXTENSIVE. SOME SPARRITE, FOSSILS, LENT. NODS SOME SALT ALONG FEW BEDDING PLANES. MAGNETITE NODS (2mm)
		NOT HAND BREAKABLE 508 mm 114 mm		COQUINA LAYER	SAME, HAS A FEW FOSSILS, VERY XTALL, BUT NOT APH. NOR CONCOIDAL. BUT V. BRITTLE. NODS ARE ~ 4cm in browny SOFT ZONES OF ARGIL. LST. MUD.

12	48	LST.			
14	48–53	NODULAR LIMESTONE (LOW CLAY; MED - CLAY; HIGH CLAY)	100 % 478 mm	(THIS INTERVAL NOT TESTED)	NOT HAND BREAKABLE 508 mm; 114 mm
	53–59	BANDED SHALEY LST.	96 % 241 mm	50%	BREAKS EASILY ARG. BANDS ARE THICKER 33 mm
16	59–61	CALCAREOUS SHALE	100 % 385 mm	69%	20 mm
	61–68	DISS. ARG. MICRITE	N A		47 mm
18	68–71	NODULAR LST (MED. CLAY; H. CLAY)	85 % 150 mm	(NOT TESTED)	31 mm
20	71–78	SHALEY LST.	80 % 154 mm	88 % 89 %	WEAK - BREAKS EASILY 12 mm
	79	NODULAR LST.	N/A		40 mm
	79–82	BIOLITHITE	100 % 375 mm		BANDED MID-SECTION
22	82–91	NODULAR LST (H. CLAY; H. CLAY; MED. CLAY)	89 % 226 mm		88 mm
24	92	DISS. ARGIL. MICRITE	N A		115 mm
	92–94	INTRAFORMATION LST. CONGLOM.	N A		120 mm
26	94	DISSEMINATED ARGILLACEOUS MICRITE	99 % 324 mm	89 %	CRUMBLY; MOST IS MASSIVE; QUITE COHESIVE; AVE = [illegible]
28	[illegible]				

	FRAGS. (NO) ORTHOS.)	... PLANES. MAGNETITE NODS (2mm)
NOT HAND BREAKABLE 508 mm 114 mm	COQUINA LAYER	SAME, HAS A FEW FOSSILS, VERY XTALL, BUT NOT APH. NOR CONCOIDAL. BUT V. BRITTLE. NODS. ARE ~ 4cm in browny SOFT ZONES OF ARGIL. LST. MUD.
BREAKS EASILY ARG. BANDS ARE THICKER 83 mm	SEMI-REGULAR BANDING SOFT - PLATY	IRREGULAR BANDING, ALTERAT: XTAL & ARG. SOME ARG. ARE VERY PLANAR, OTHERS WAVY. FINE PYRITE. BECOMING LIKE A LIME MUDSTONE.; ALMOST FISSILE.
20 mm	FINE LAMIN.- BANDING. NEAR FISSILE	MOD. CALC. SIMILAR TO BENTONITE + NO CRYSTALIZATION RUSTY BEDDING IN PLACES SOFT GREEN. "FISSILE" TO WELL LAMINATED
47 mm	NO BEDDING	LT. GREENISH, FIRMER, LIKE V. WEATH. ARG. LIME MUD
31 mm		SAME NODULAR. HIGH MATRIX CONTENT (20-30%). DISS. MAGN. THROUGHOUT A FEW DETRITAL LAYERS.
WEAK - BREAKS EASILY 12 mm	BANDED PLATEY	BANDED - LENSEY & NODS, OF HARD XTAL. LST. BREAKS ALONG THE PLANAR ARG. BANDS & LIKE SHALEY ARG. IS SL. GREEN & DARKER
40 mm		BASE IS HIGH ARG. SOF V. WEAK (AFTER DRYING)
BANDED MID-SECTION	DETRITAL LAYERS & ARGIL. LENSES → PLATEY TO CRUMBLY.	V. WELL CRYSTALLIZED WITH SPARRY FOSSILS & DETRIT. SOME ARG. STREAKS → CRUMBLES.
88 mm	NO BEDDING; V. IRREGULAR, BREAKS ALONG NODULES. JOINT DIP = 70°- VERT, MED PLANAR V. ROUGH - DISCONT.	SAME NODULAR (60% OF ROCK) ROUNDED 1-2 cm TO IRREGULAR ZONES OF XTAL. LIMESTONE. STRONGLY CALC. IN BOTH NODS. & MATRIX.
115 mm	MASSIVE	MOD. CALC. LIME MUDST. A FEW FOSSILS? PELOIDS
120 mm	MASSIVE	NODS ARE DISTINCT, V. REGULAR ← SALT & VUG IN FOSSILS.
CRUMBLY MOST IS MASSIVE QUITE COHESIVE [illegible]	BEDDING PARTING ARE MED. ROUGH, BUT MOSTLY NO BEDDING	LIKE LIME MUDST. AT PLACES ARE DEFINITE CORAL FRAGS, REPLACED BY SPARITE, ALSO INDET. FRAGS. SCATTERED NODS (1mm) OF PYRITE WITH MAGN. @ 26.8 m SHOWS WELL THE ORGANIC ORIGIN PLUS ? BIOTURBATION? BECOMES MORE FOSSIL- MOD. &

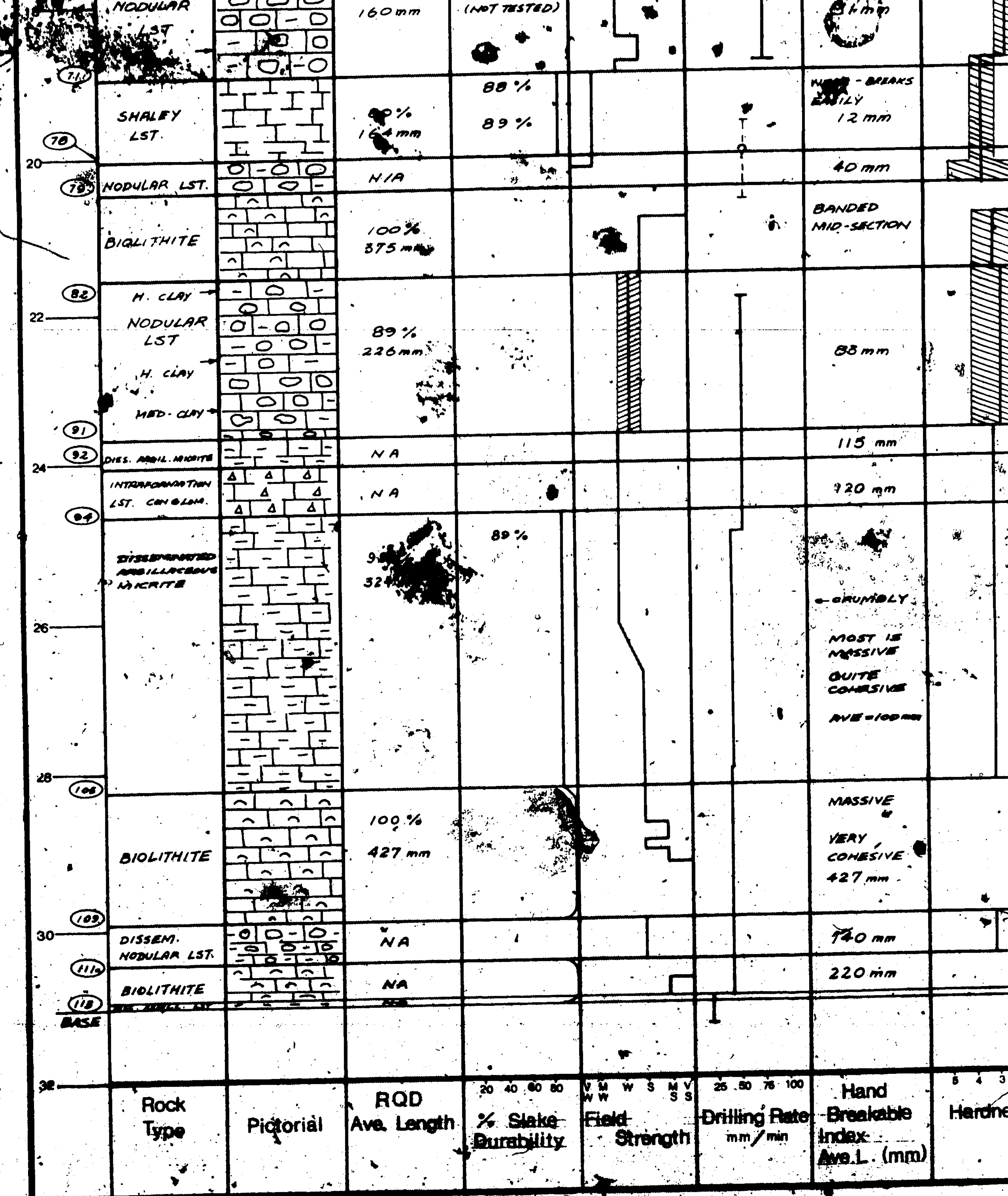


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Figure 11 Lithological and Geotechnical Log of C

Field Strength (VW W M S VS)	Drilling Rate mm/min (25 50 75 100)	Hand Breakable Index Ave.L (mm)	Hardness (5 4 3 2 1)	Bedding Joints	Lithology Description
		31 mm			DISS. MAGN. THROUGHOUT. A FEW DETRITAL LAYERS.
		WEAK - BREAKS EASILY 12 mm		BANDED PLATEY	BANDED - LENSEY & NODS, OF HARD XTAL. LST. BREAKS ALONG THE PLANAR ARG. BANDS → LIKE SHALEY ARG. IS SL. GREEN & DARKER
		40 mm			BASE IS HIGH ARG. OF V. WEAK (AFTER DRYING)
		BANDED - MID-SECTION		DETRITAL LAYERS & ARGIL. LENSES → PLATEY TO CRUMBLY	V. WELL CRYSTALLIZED WITH SPARRY FOSSILS & DETRIT. SOME ARG. STREAKS → CRUMBLES.
		88 mm		NO BEDDING; V. IRREGULAR, BREAKS ALONG NODULES. JOINT DIP = 70°- VERT. MED PLANAR V. ROUGH - DISCONT.	SAME NODULAR (60% OF ROCK) ROUNDED 1-2 cm. TO IRREGULAR ZONES OF XTAL. LIMESTONE. STRONGLY CALC. IN BOTH NODS. & MATRIX.
		115 mm		MASSIVE	MOD. CALC. LIME MUDST. A FEW FOSSILS ? PELOIDS.
		120 mm		MASSIVE	NODS ARE DISTINCT, V. ANGULAR → SALT & VUG IN FOSSILS.
		→ CRUMBLY. MOST IS MASSIVE. QUITE COHESIVE. AVE = 100 mm		BEDDING PARTING ARE MED. ROUGH, BUT MOSTLY NO BEDDING	LIKE LIME MUDST. AT PLACES ARE DEFINITE CORAL FRAGS. REPLACED BY SPARITE, ALSO INDET. FRAGS. SCATTERED. NODS (1mm) OF PYRITE WITH MAGN. @ 26.8 m SHOWS WELL THE ORGANIC ORIGIN PLUS ? BIOTURBATION ? BECOMES MORE FOSSIL - MOD. & ALSO ARGIL.
		MASSIVE. VERY COHESIVE 427 mm		TAPPY JOINT VERT, SMOOTH, PLANAR, ALTHO. SPLITS INTO SEVERAL SMALL FRACS. TIGHT, TINY.	FINALLY CHANGING INTO WELL-CRYSTALLIZED CEMENTED FOSSIL - LIMESTONE. FRESH PYRITE REPLACES A FEW FOSSILS. SOME SALT, HARD TO V. HARD & V. CEMENTED. V. CALC; LOTS OF SPARITE.
		140 mm			NODULES BUT FIRM & COHESIVE LIKE LIME MUDSTONE, WITH. LST SAND
		220 mm			V. FOSSIL. V. CALC.

...hological and Geotechnical Log of Corehole WWI

6 of 6

TYPE • SUB-TYPE	CLAY CONTENT	FABRIC	GRAIN SIZE	STRENGTH	OUTCROP FEATURES	COLOR
1. Massive Crystalline Limestone						
a. Aphanitic	very low	Conchoidal fracture. Angular breccia with little matrix	sub-visible <10	med. strong		Light tan to pinkish
b. Micrite	very low	Even crystalline sugary appearance	very fine <30	med-very strong	resistant, blocky	Light to medium grey
c. Biolithite	very low	Fossil debris in crystalline matrix with cement	very fine <30	very strong	resistant, blocky	Light med. grey
d. Coquina	extremely low	Purely fossil debris; well cemented	coarse >>2mm	med strong	resistant, platy	Light med. grey
2. Nodular Limestone						
a. Low-Clay Nodular	low	Matrix <20% Rounded to angular fine crystalline nodules (<3cm) in soft & dark fine matrix	[illegible] <100	strong-weak	rubbly	Light med grey
b. High-Clay Nodular	med.	Same as low-clay, but matrix forming >20% of rock	fine-v. fine <100	med-very weak	very rubbly	med. dark grey
3. Shaly Limestone						
a. Green Shale	high	laminated, partly fissile, calcareous	sub-visible <10	very weak	soft, plastic and clay like	med. dark greenish gray
b. Calcareous Shale	high	Banded, fine grain, bands of light calcareous and dark clayey, 1-3cm thick	very fine <30	weak-med. weak	thin hard plates of limestone between soft clayey bands.	Medium dark grey
c. Argillaceous Limestone	med.	Fine grained limestone with laminae and bands	fine-v fine	weak	thick plates of limestone	light-med. grey
d. Disseminated Argillaceous Micrite	med.	Evenly fine grained micrite with worm burrows; soft.	fine <100	strong		med. grey

Clay: extremely low=<2% very low=<5% low=5-15% medium=15-35% high=>35%

Figure 12. Table of Rock Types of the Waterways Formation.

ALLOCHEM COMPOSITION	ALLOCHEMICAL ROCKS		ORTHOCHEMICAL ROCKS
	SPARRY CALCITE CEMENT	MICROCRYSTALLINE CALCITE MATRIX	III MICROCRYSTALLINE CALCITE LACKING ALLOCHEMS
			Micrite
INTRACLASTS	Intrasparite	Intramicrite	Dismicrite
OOLITES	Oosparite	Oomicrite	AUTOCHTHONOUS
FOSSILS	Biosparite	Biomicrite	REEF ROCKS
PELLETS	Pelsparite	Pelmicrite	Biolithite

Figure 13. Table of Limestone Classification (after Folk).

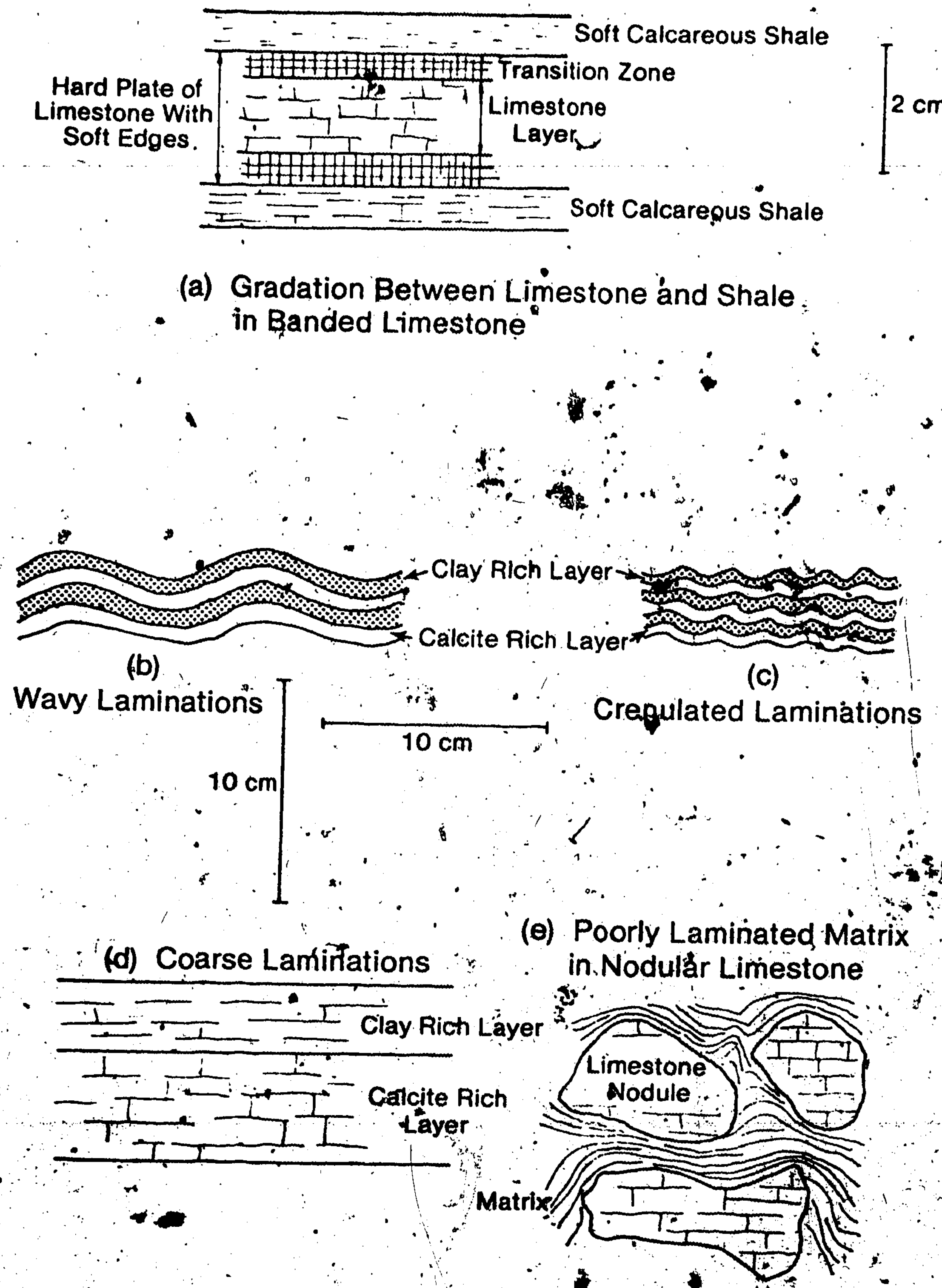


Figure 14. Banding and Lamination in Argillaceous Rocks.

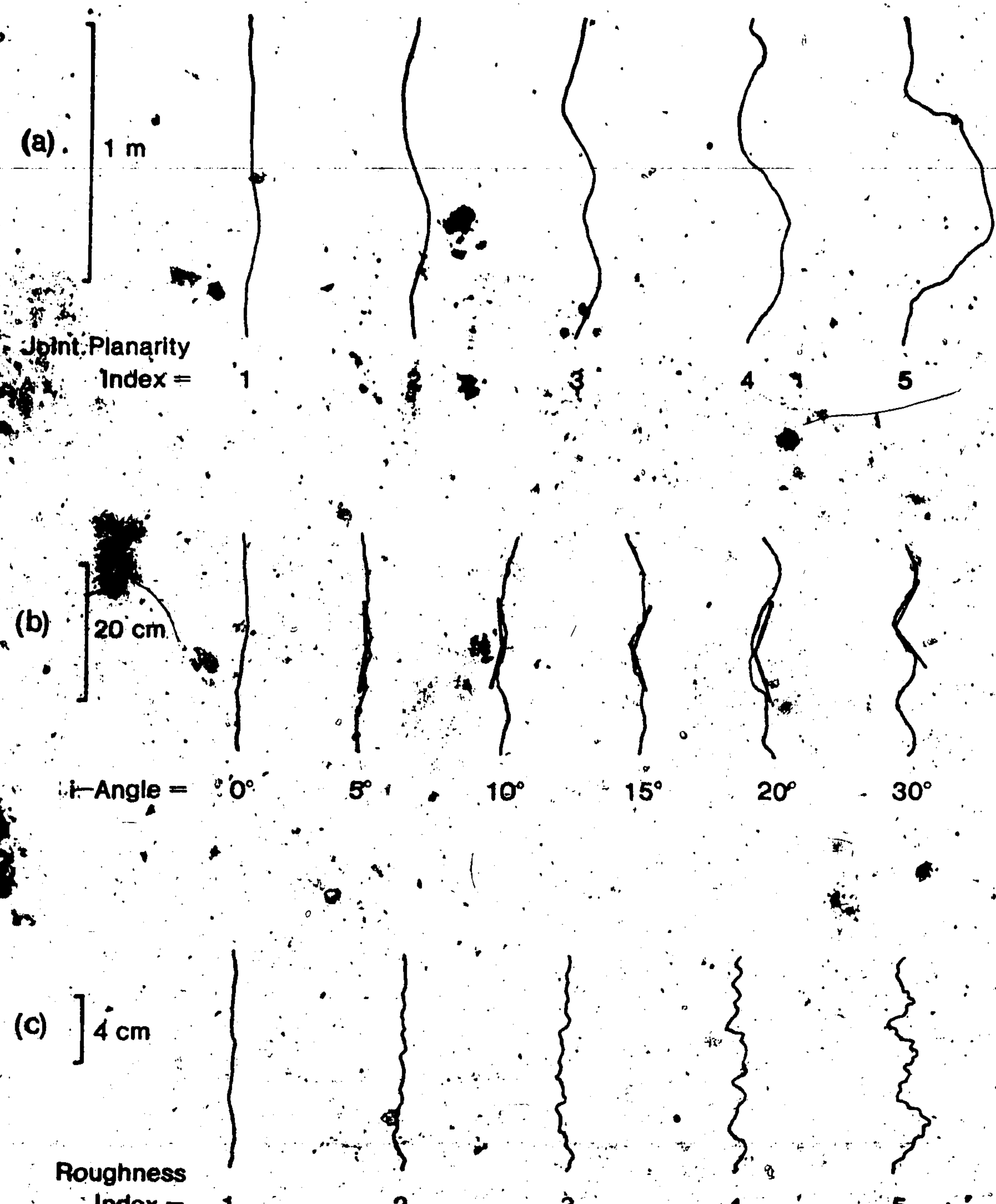


Figure 15. Illustrations of Joint Surface Irregularity Indices.
a) Planarity b) Waviness c) Roughness.

ROCK TYPE ROCKS	MASSIVE CRYSTALLINE LIMESTONE	NODULAR LIMESTONE	SHALY
Spacing	.7 - 3.0 meters	2.6 meters	(undefined very fractured)
Regularity	moderately to very good	poor to very poor	(undefined very fractured
Planarity	2.3 (moderately planar)	4.0 (very non-planar	(undefined very fractured
Length	.7 - 3.0 meters	0.3 - 2.0 meters	(0.1-0.3 M (irregular)

Figure 16. Table of Joint Characteristics in Three Waterways Formation Lithologies.

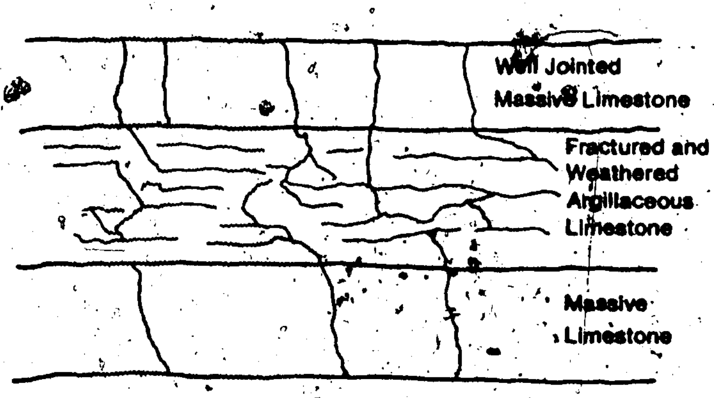


Figure 17. Jointing in Weak and Strong Strata

	AZIMUTH (AVERAGE)	RANGE	GENERAL STRIKE DIRECTION	NUMBER OF JOINTS
Set I	172.3°	159-190°	N - S	5803 locations
Set II	138.2°	122-160°	NW - SE	1560 Locations
Set III	93.7°	75-114°	E - W	12304 locations
Set IV	39.7°	15-74°	NE - SW	12804 locations

Figure 18. Table of Joint Set Orientations.

Joint Azimuths, Mountain Outcrop, 211 Readings

Set II 122° – 160° (300° – 340°)

Set III 090° – 114° (270° – 294°)

Set IV 026° – 075° (206° – 255°)

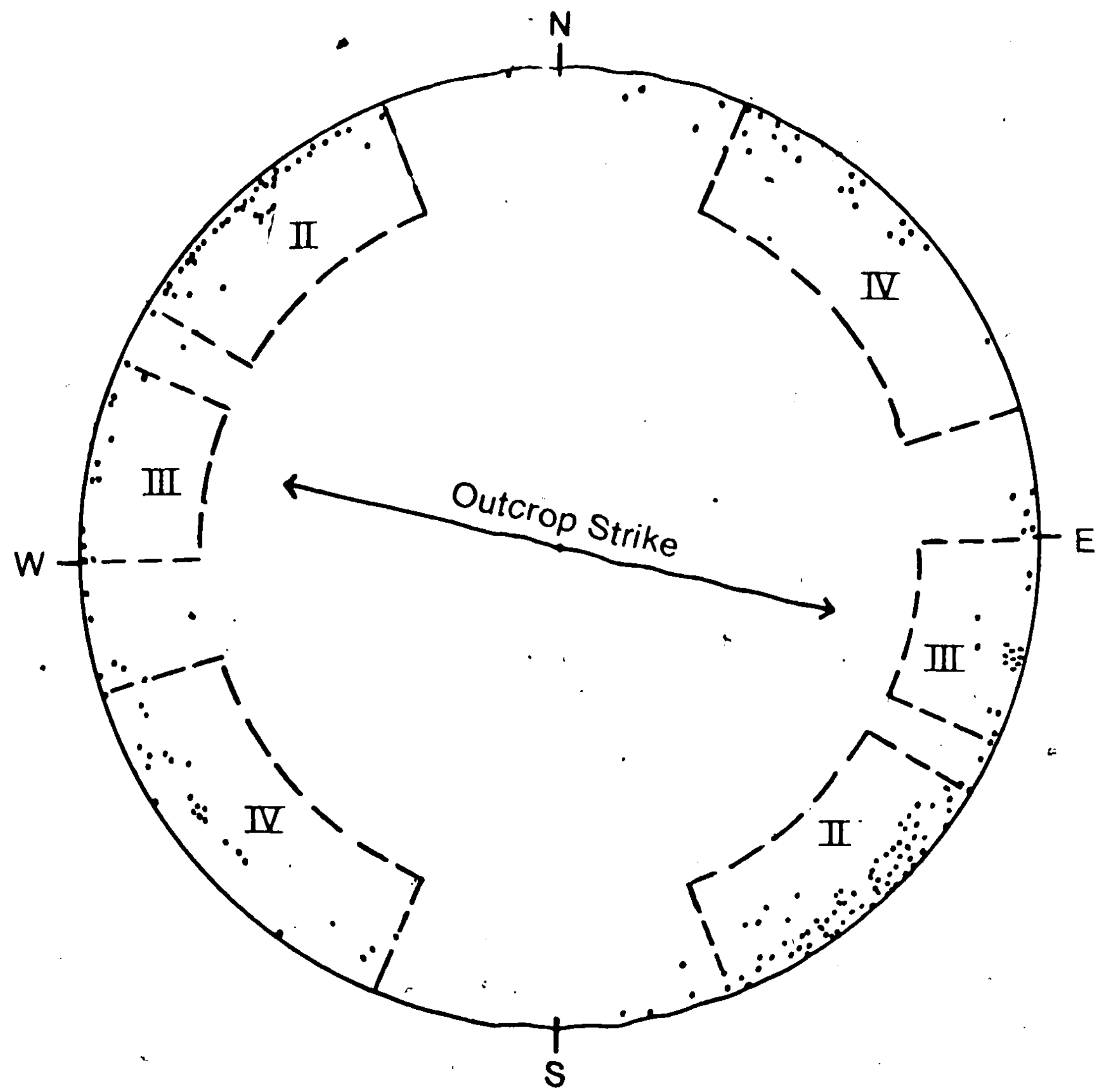


Figure 19a. Stereonet of Outcrop Joints, Moberly Member, Waterways Formation.
(Not corrected for directional bias).

Joint Azimuths, Moberly Outcrop, 76 Readings

Set I 158° – 178° (338° – 358°)

Set II 124° – 152° (304° – 332°)

Set III 080° – 106° (260° – 286°)

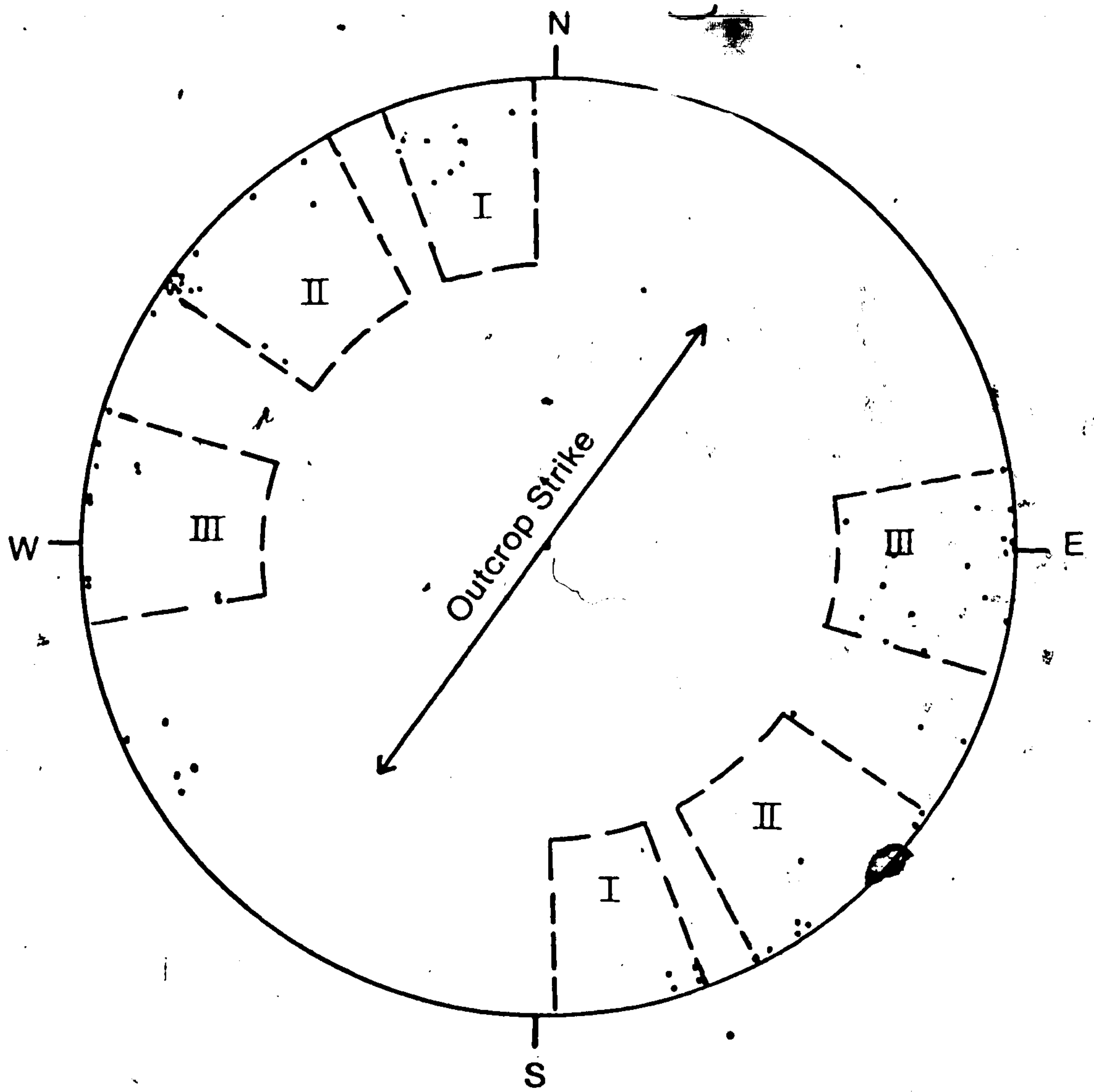


Figure 19b. Stereonet of Outcrop Joints, Moberly Member Waterways Formation.

(Not corrected for directional bias).

Joint Azimuths, Stony Outcrop, 110 Readings

Set I	160 – 190	(340 – 010)
Set III	075° – 105°	(255° – 285°)
Set IV	015° – 056°	(195° – 236°)

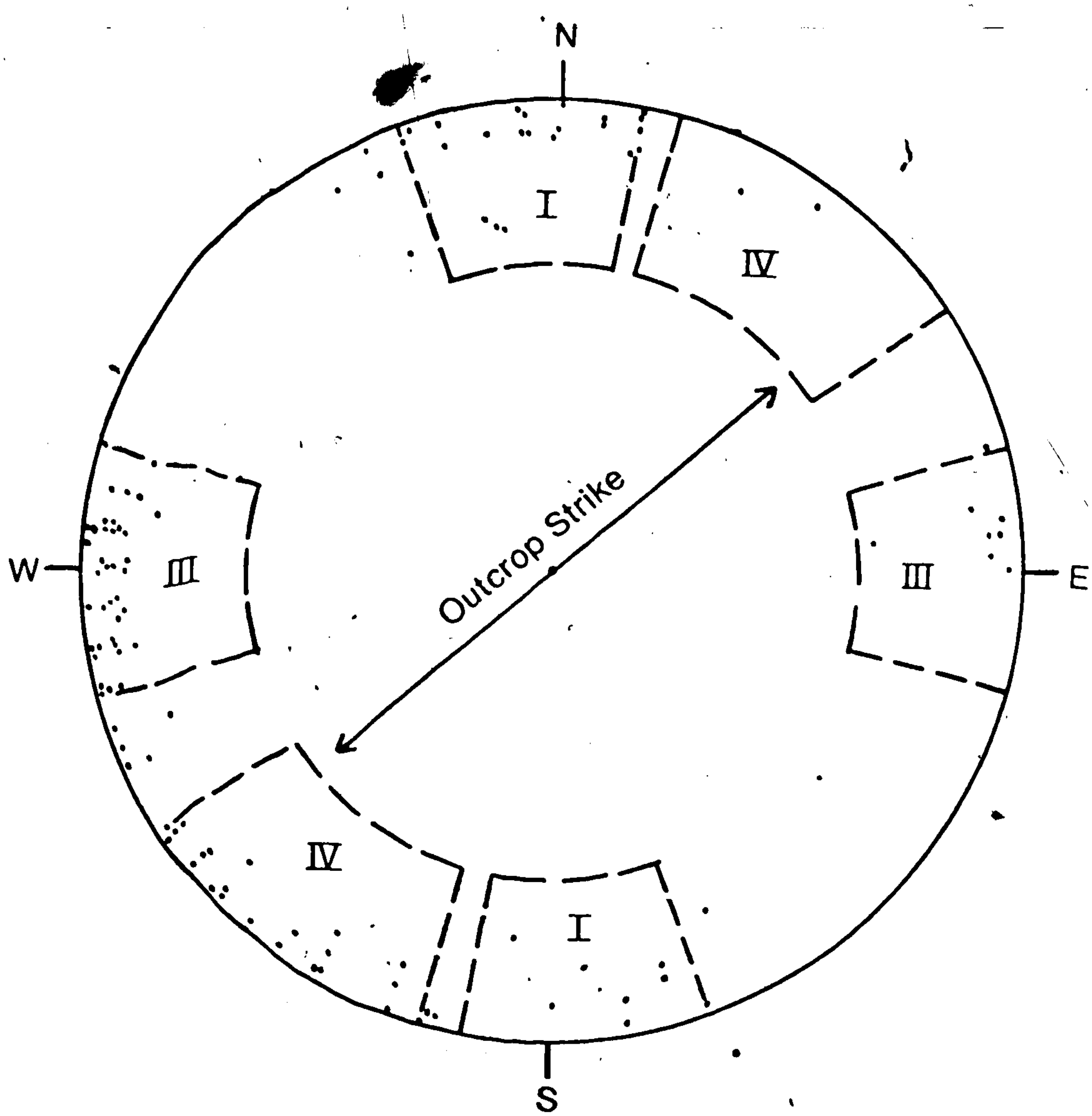


Figure 19c. Stereonet of Outcrop Joints, Moberly Member Waterways Formation.

(Not corrected for directional bias).

Joint Azimuths, Mackay Outcrop, 105 Readings

Set I	170° – 190° (350 – 010°)
Set II	125° – 160° (305° – 340°)
Set IV	015° – 065° (195° – 245°)

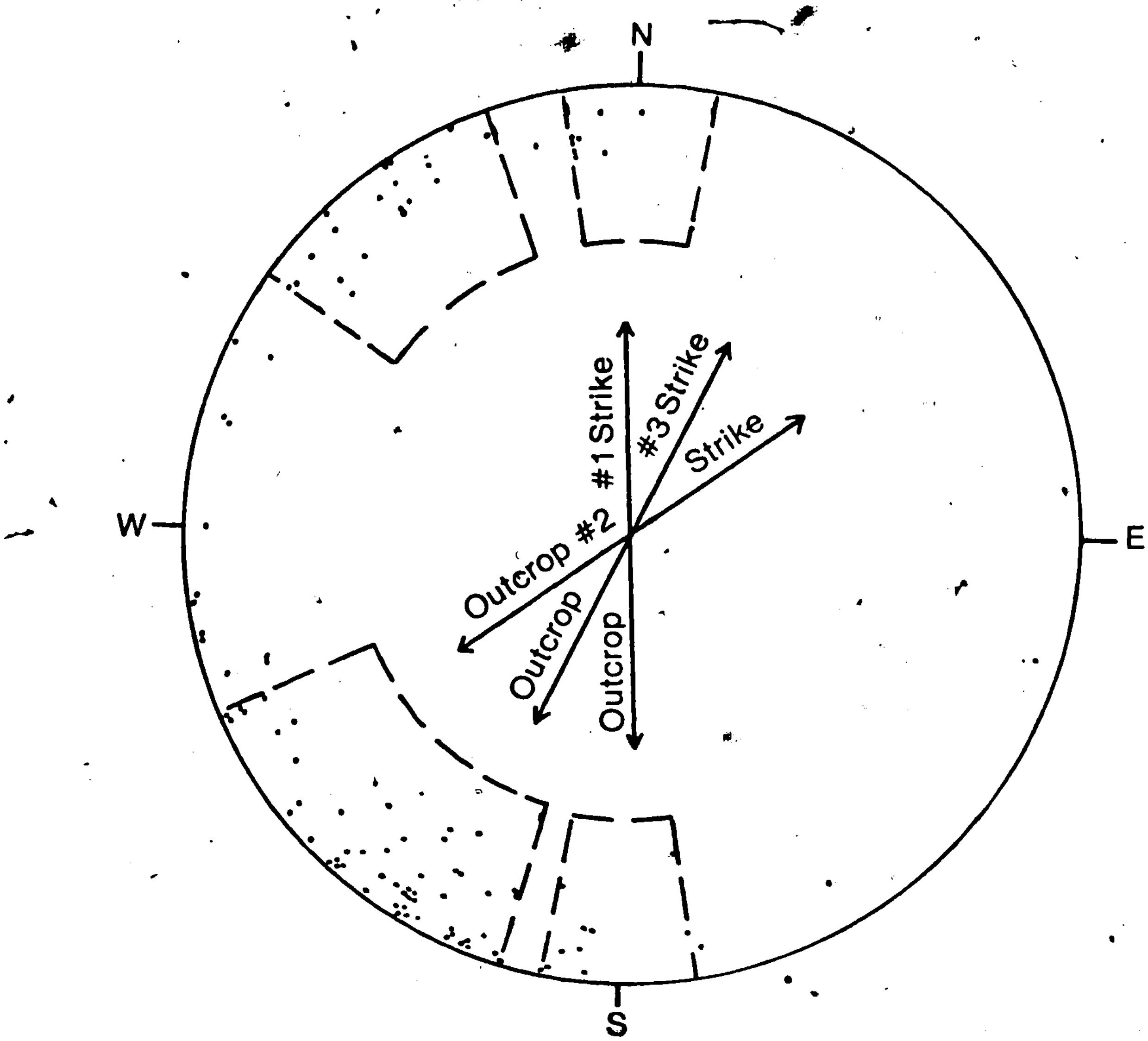
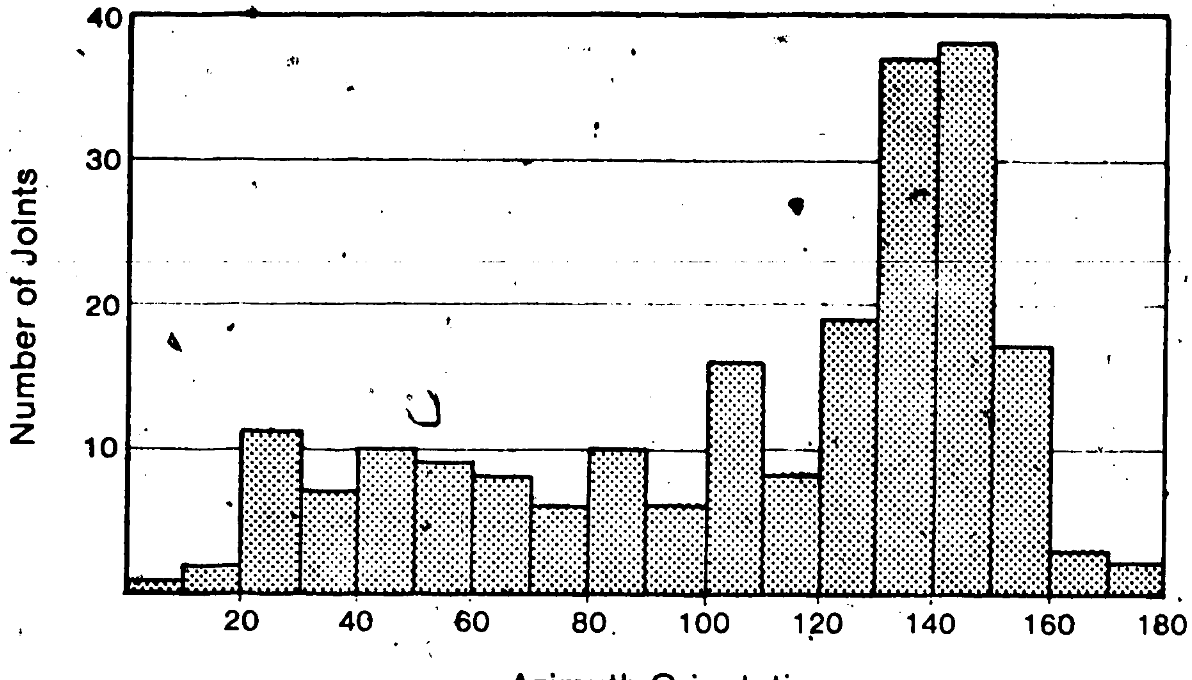
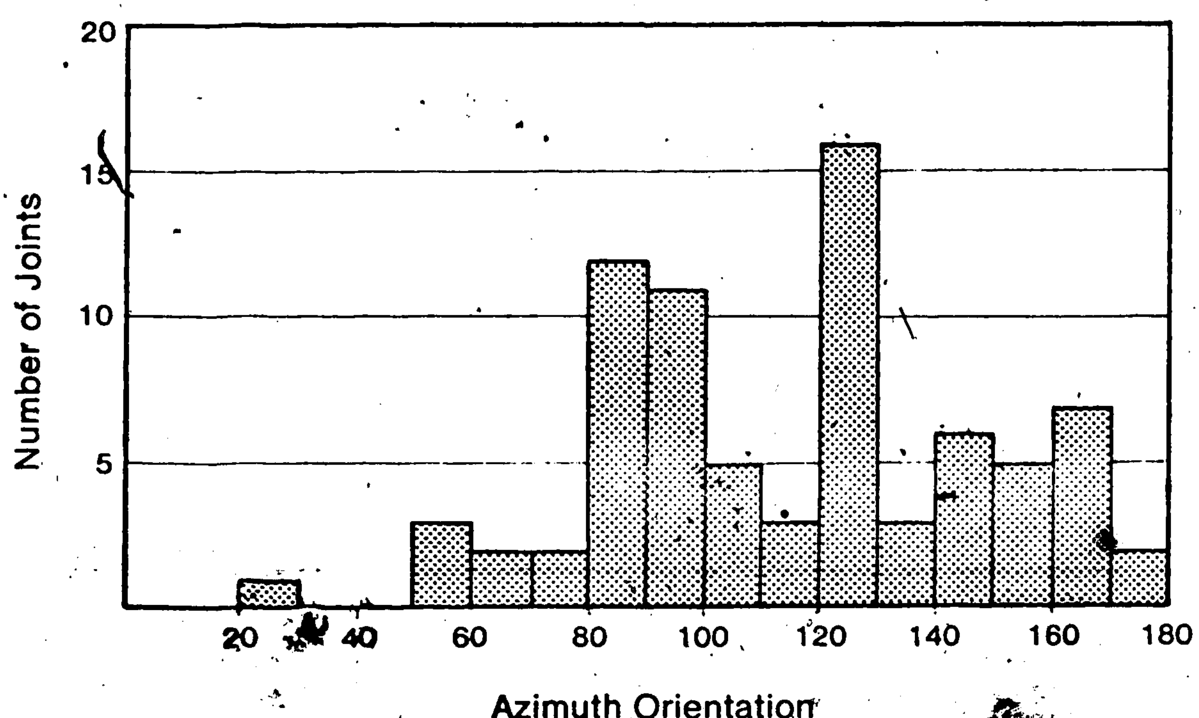


Figure 19d. Stereonet of Outcrop Joints, Moberly Member Waterways Formation.

(Not corrected for directional bias).



(a) Mountain Outcrop 210 Readings



(b) Moberly Outcrop 77 Readings
(Values on Boundary Fall Into Lower Group)

Figure 20 a,b. Frequency Chart of Joints in Outcrops of Waterways Formation.

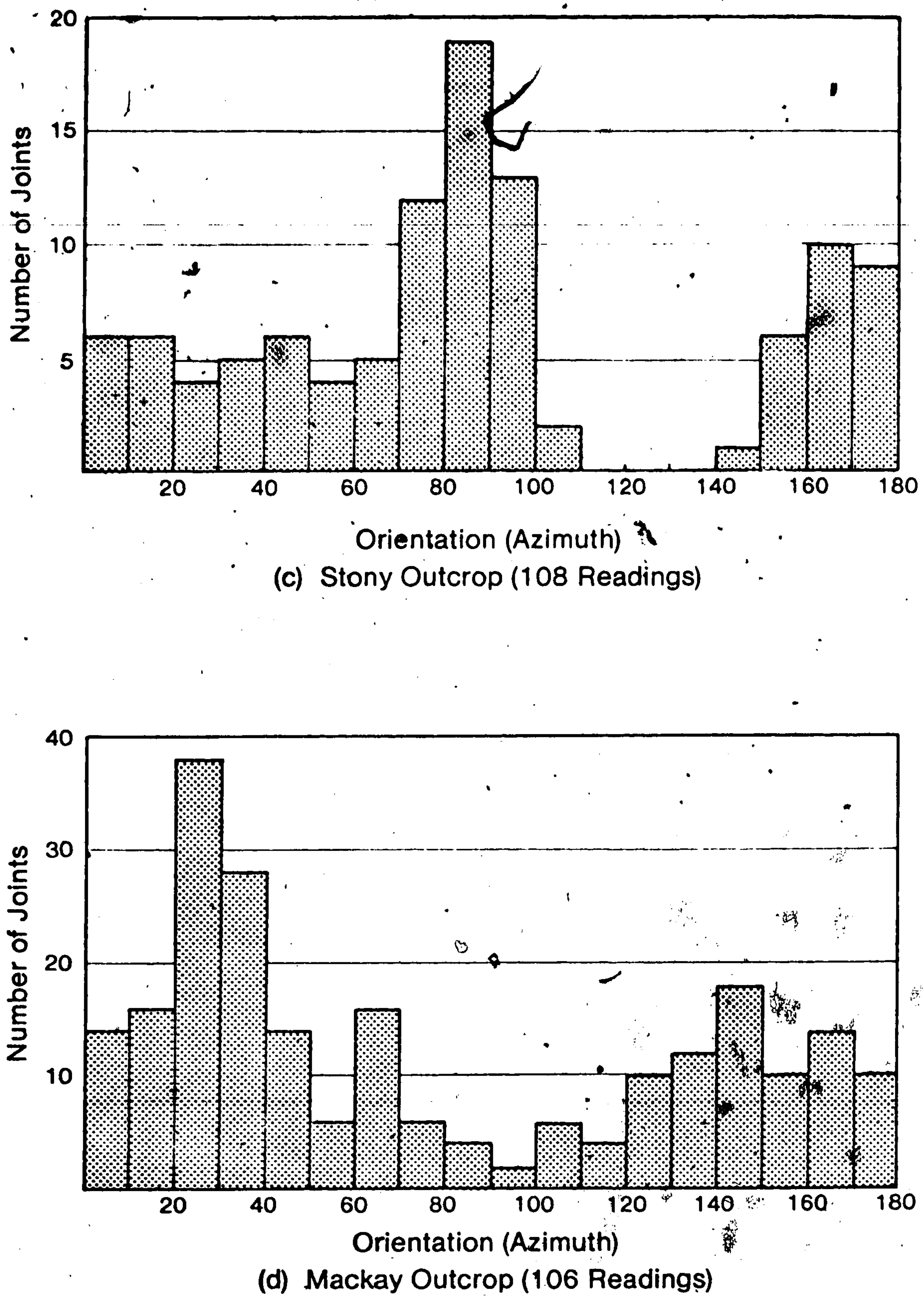


Figure 20 c,d. Frequency Chart of Joints in the Waterways Formation.

SETS	MACKAY	MOUNTAIN	MOBERLY	STONY
		ORIENTATION / NUMBER		
I	360°±10°/ 18		348°±9 / 13	355°±15 / 27
II	322°±17°/ 23	321°±19 / 47	318°±14/ 25	
III		282°±12 / 12	273°±13/ 29	270°±15 / 48
IV	220°±25°/ 50	230°±24 / 29		215°±20 / 25
COMMENTS	Others = 5 Total =105	108 orient only Others = 5 Total =211	Others = 3 Total = 76	Others = 10 Total =110
		SPACING OF JOINTS (metres)		
I	6.27 m		4.20	2.45 m
II	2.42 m	0.67 m*'	3.16 m	
III		1.70 m*'	2.08 m	1.67 m
IV	2.17 m	0.63 m*'		4.08 m
		PLANARITY INDEX		
I	3.1		2.5	3.1**' 3.0**'
II	2.8	1.3*'	4.1	
III		1.6*'	3.4	2.65**' 2.4***
IV	3.2	1.4*'		2.5**' 3.0**'
		ROUGHNESS INDEX		
I	3.25		2.8	2.4**' 2.8***
II	3.1	3.6*' 3.7**	2.7	
III		3.0*' 3.0**	2.9	2.5**' 2.4***
IV	3.0	3.2*'		3.0**' 2.4***
		WAVINESS INDEX (i-Angle)		
I	19°		23°	22°**' 19.4***
II	18.4°	7.7°*' 14.4°**	24°	
III		11.3*' 24**	19.6°	17°**' 22***
IV	22°	12.2*' 30**		13°**' 13.6°***
		DIP (with Standard Deviation)		
I	86.8°S		81°S(±4°)	87°S
II	88°W	89°E*'	85°W(±11.8°)	87.6°E**'
III		90°*'	85°W(±16.6°)	88.3°E**'
IV	87.6E(±8.3)	88.8°E*'		
		LENGTH (metres, or lithologic units)		
I	2.04 metres		1.67	1.59
II	2.43 metres	1.35	1.13	
III		1.42 metres	1.71	2.0
IV	2.19 metres	1.10		1.37
	SURFACE STAINING			
I	No staining of joints-		33% rusty	Flood Area stained. One calcite-filled vein 0.5 cm wide
II		55% rusty	16% rust stained	
III	Possible flood area	42% rusty, tarry or clayey	19% rusty	
IV		72% calcite filled, rusty or tarry		

Comments *2= Unit 2, Mountain *4= Unit 4, Mountain Outcrop
**2= Unit 2, Stony **4= Unit 4, Stony Outcrop

Figure 21 Table of Joint Set Characteristics at Each of Four Outcrops.

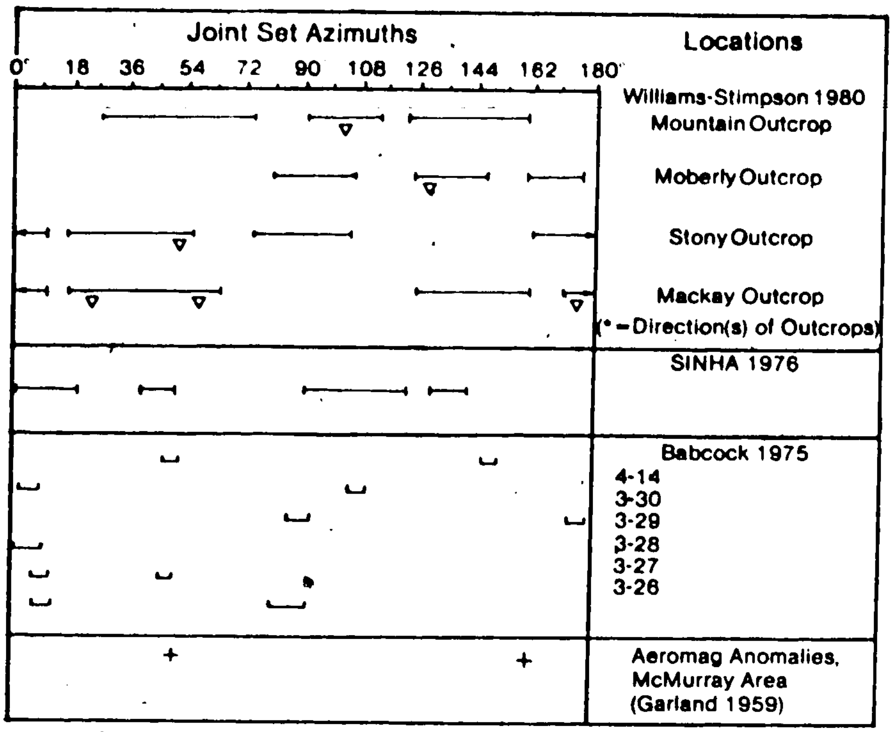


Figure 22. Joint Orientations in Moberly Member Outcrop, Defined By Various Authors (with data from Babcock, 1975).

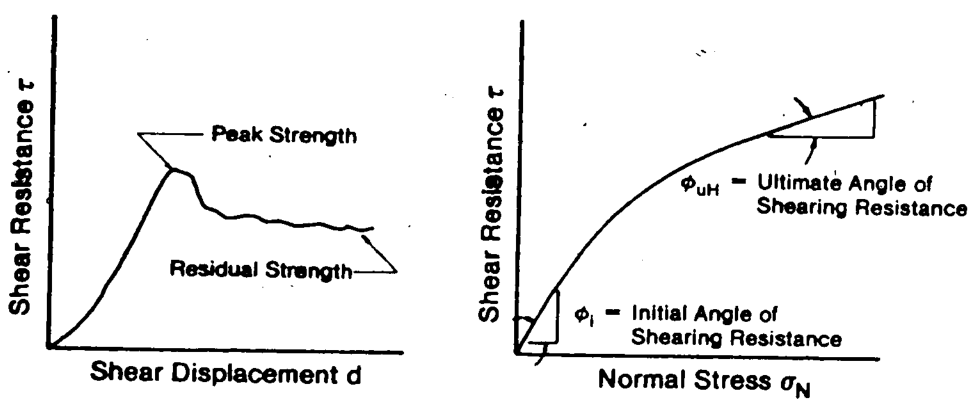


Figure 23. The Relation of Shear Strength to :
i) Displacement and ii) Normal Stress

Specimen Number	4b	8b	9/10-1	9/10-2	40b	411a	68•2
Rock Type and Surface Condition	Biolithic v weathered fossils, porous but firm.	Nodular micritic. Surface partly tarry	Nodular micritic. Hard, tough tarry and rough.	Aphanitic. Hard and strong. One surface less tarry sl weath	Medium-clay Nodular. Moderately hard&tough	Aphanitic. Sl weathered, med soft. Tar on one surface only.	Nodular with clay partings. Mod strong.
Test Area of Joint	$4700 mm^2$	$3750 mm^2$	$3450 mm^2$	$5020 mm^2$	$5070 mm^2$	$3750 mm^2$	$4390 mm^2$
Range of Normal Stress	22-349 KPa	27-463 KPa	30-901 KPa	20-632 KPa	25-281 KPa	27-682 KPa	23-315 KPa
No. of tests /specimen	6	8	9	13	6	10	6
ϕpeak	61°	73°	65°	71/61°	74°	75°	63°
ϕfinal	32°	44°	32°	26/54°	49°	25°	36.5°
Roughness Coeff	2	5	5	3	4	4	
Time Submerged	24 hrs.	40 hrs.	26 hrs.	11 hrs.	16 hrs.	22 hrs	24 hrs.
Depth of Sample	0.5 m	1.1 m	1.4 m	1.5 m	8 m	8.2 m	18.5 m
Condition of rock while testing.	Asperities slowly crushed.	Asperities quickly crushed.	Surface only slowly ground up.	Remained firm and tarry. Retested from zero.		Surface crushed slowly-then severely	Clay surface became soft and mushy.

Figure 24. Table of Joint Direct Shear Test Conditions and Results.

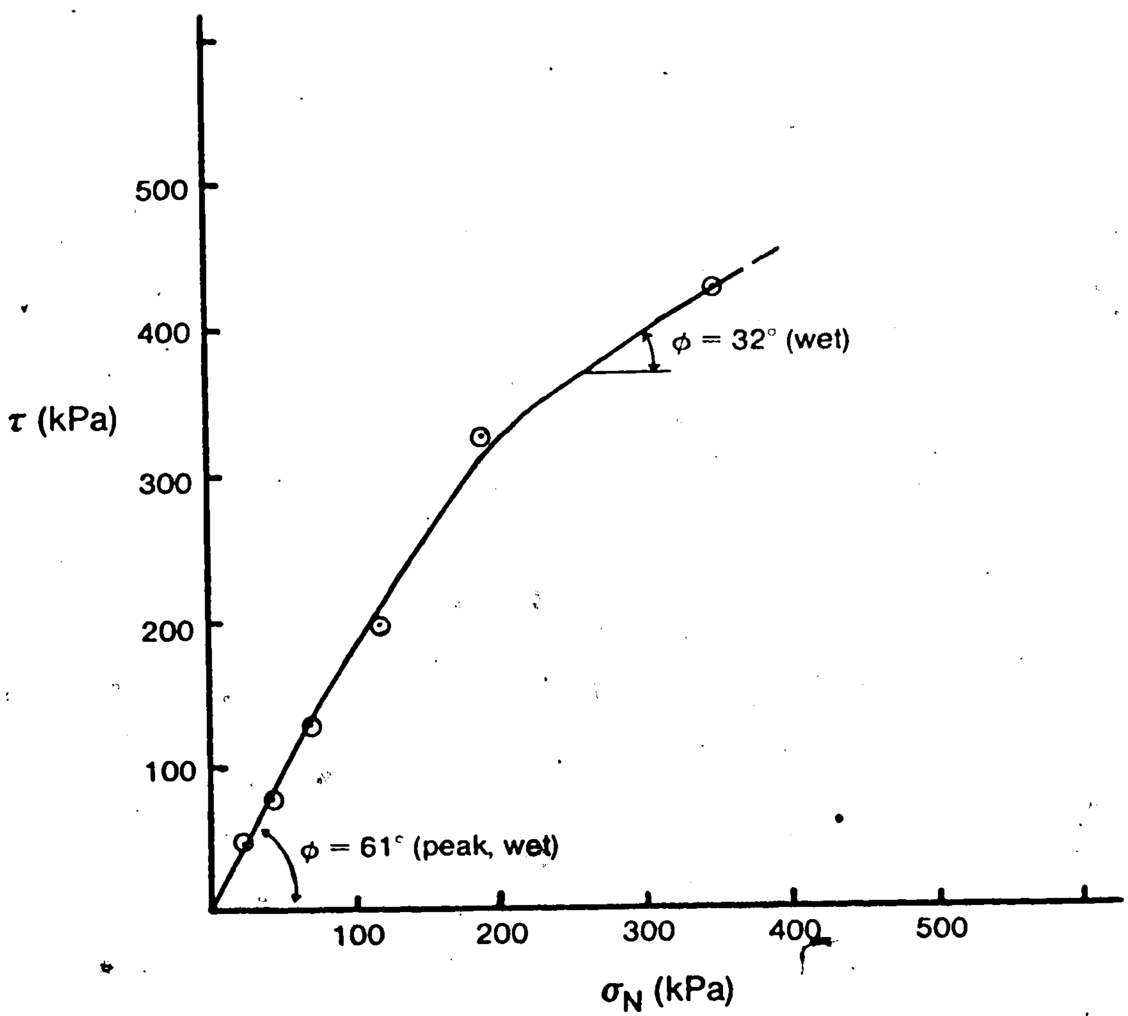


Figure 25a. Shear Strength Versus Normal Stress Along Joint Specimen # 4b.

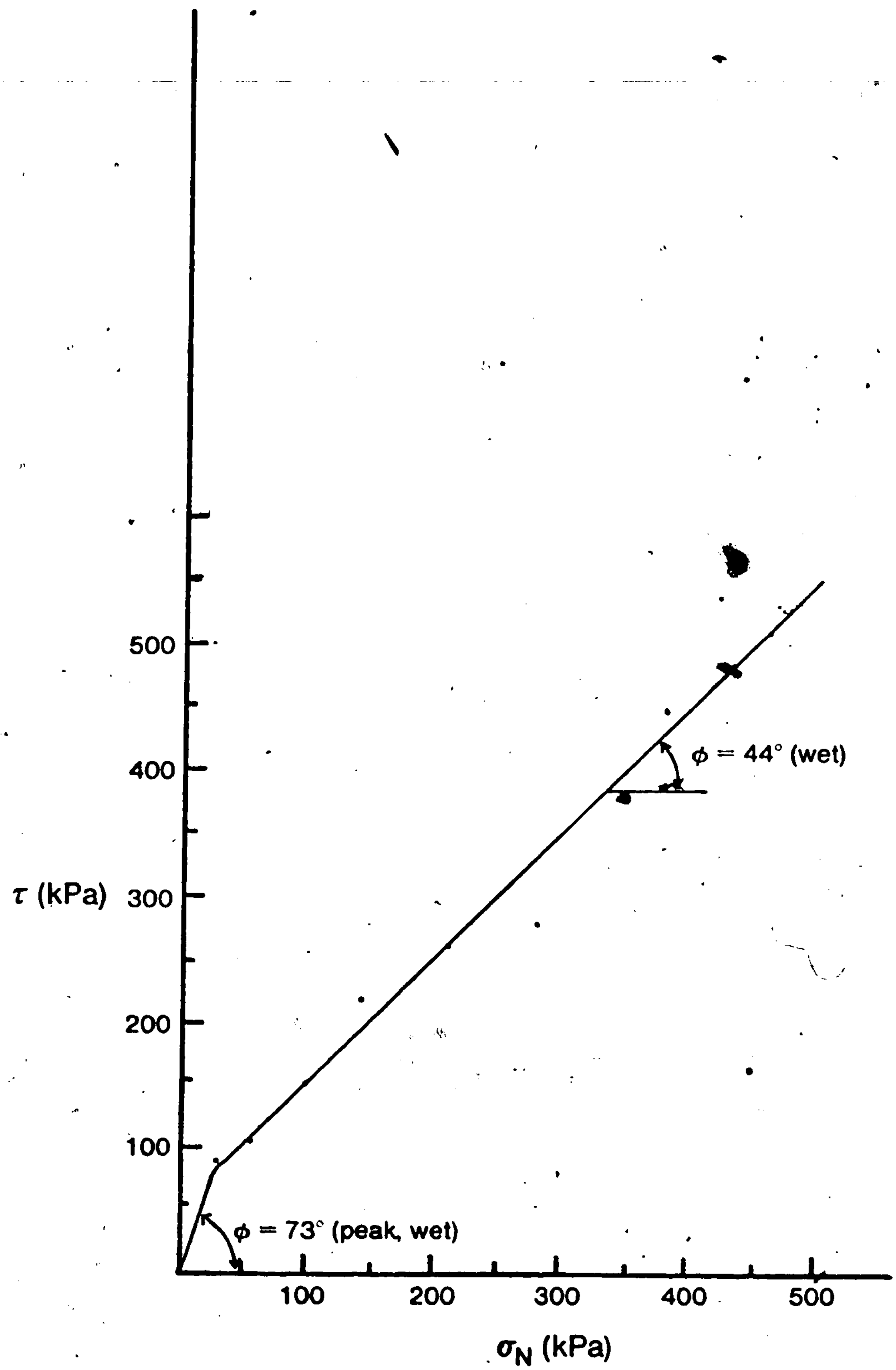


Figure 25b. Shear Strength Versus Normal Stress Along Joint Specimen # 8b.

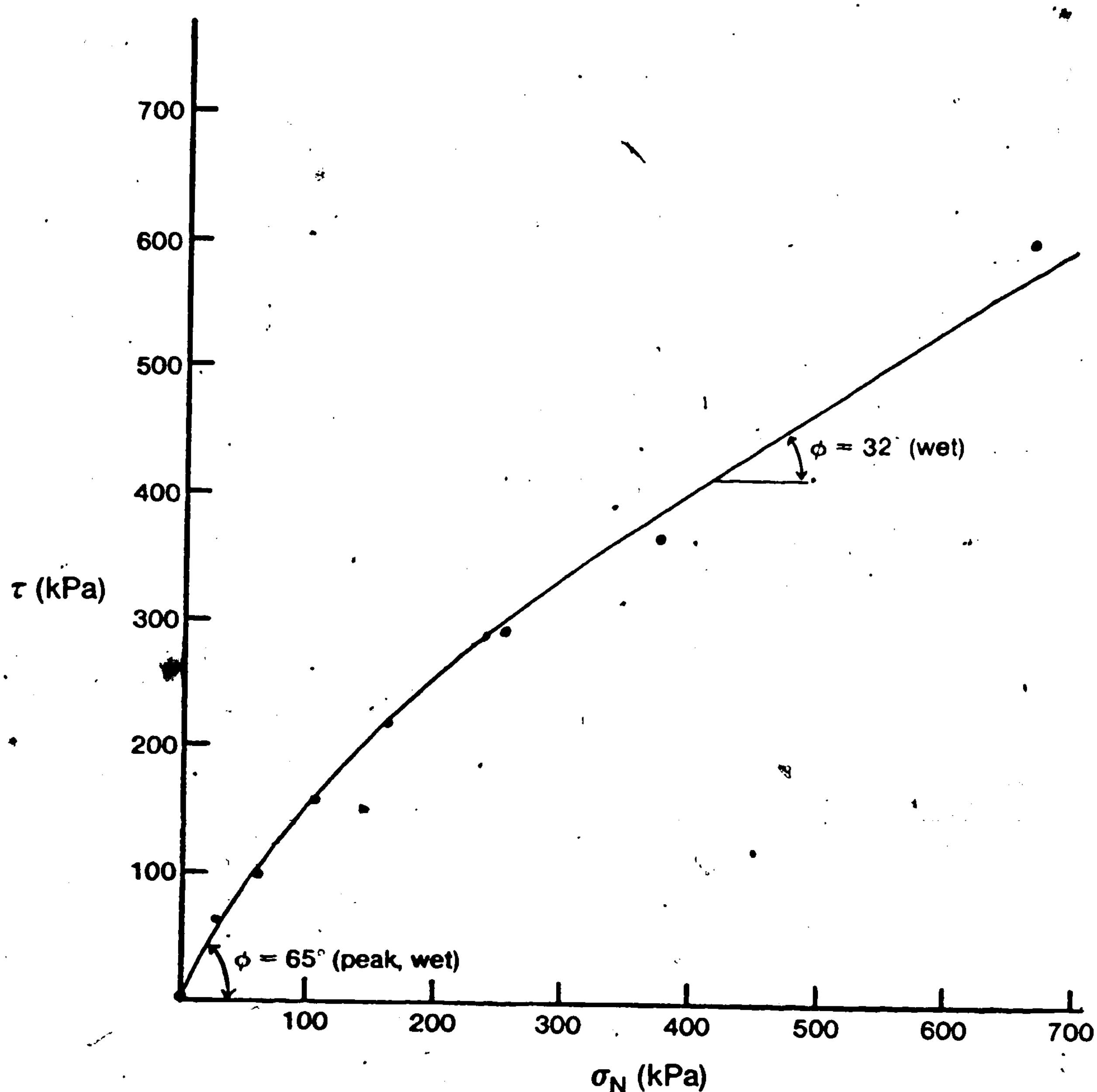


Figure 25c. Shear Strength Versus Normal Stress Along Joint Specimen # 9/10-1.

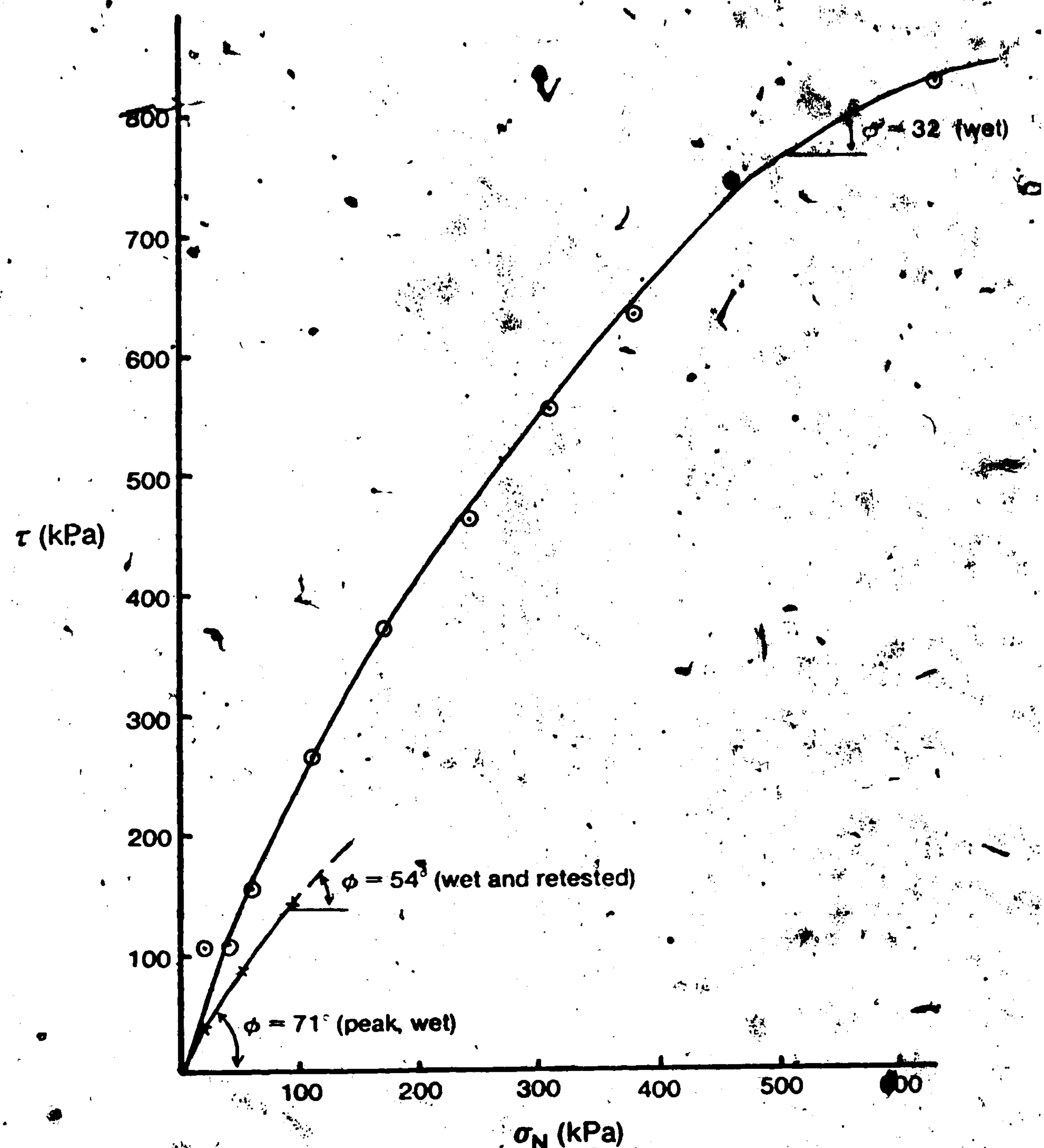
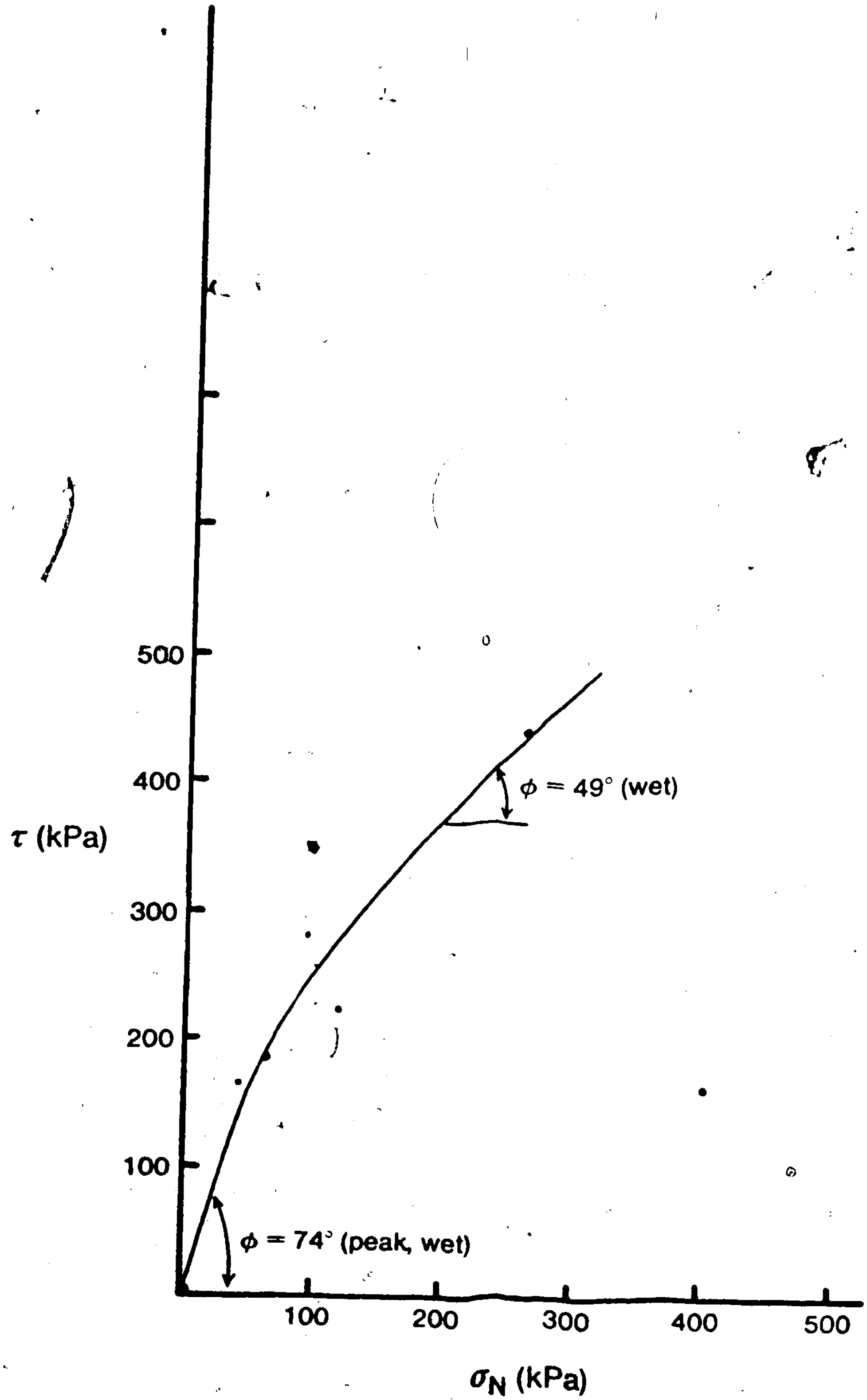


Figure 25d. Shear Strength Versus Normal Stress Along Joint Specimen # 9/10-2.



25e. Shear Strength Versus Normal Stress Along Joint Specimen # 40b.

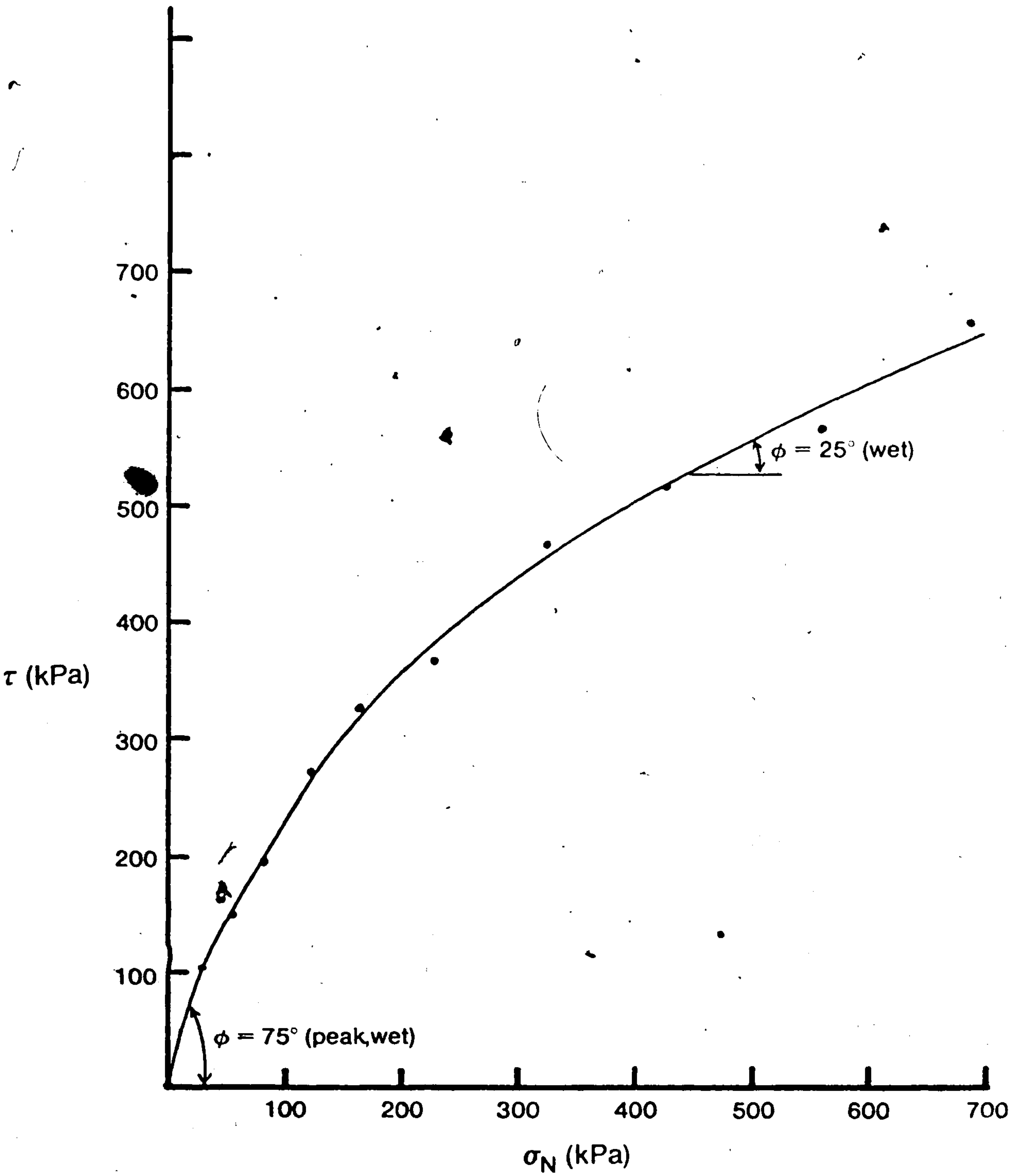


Figure 25f. Shear Strength Versus Normal Stress Along Joint Specimen # 41a.

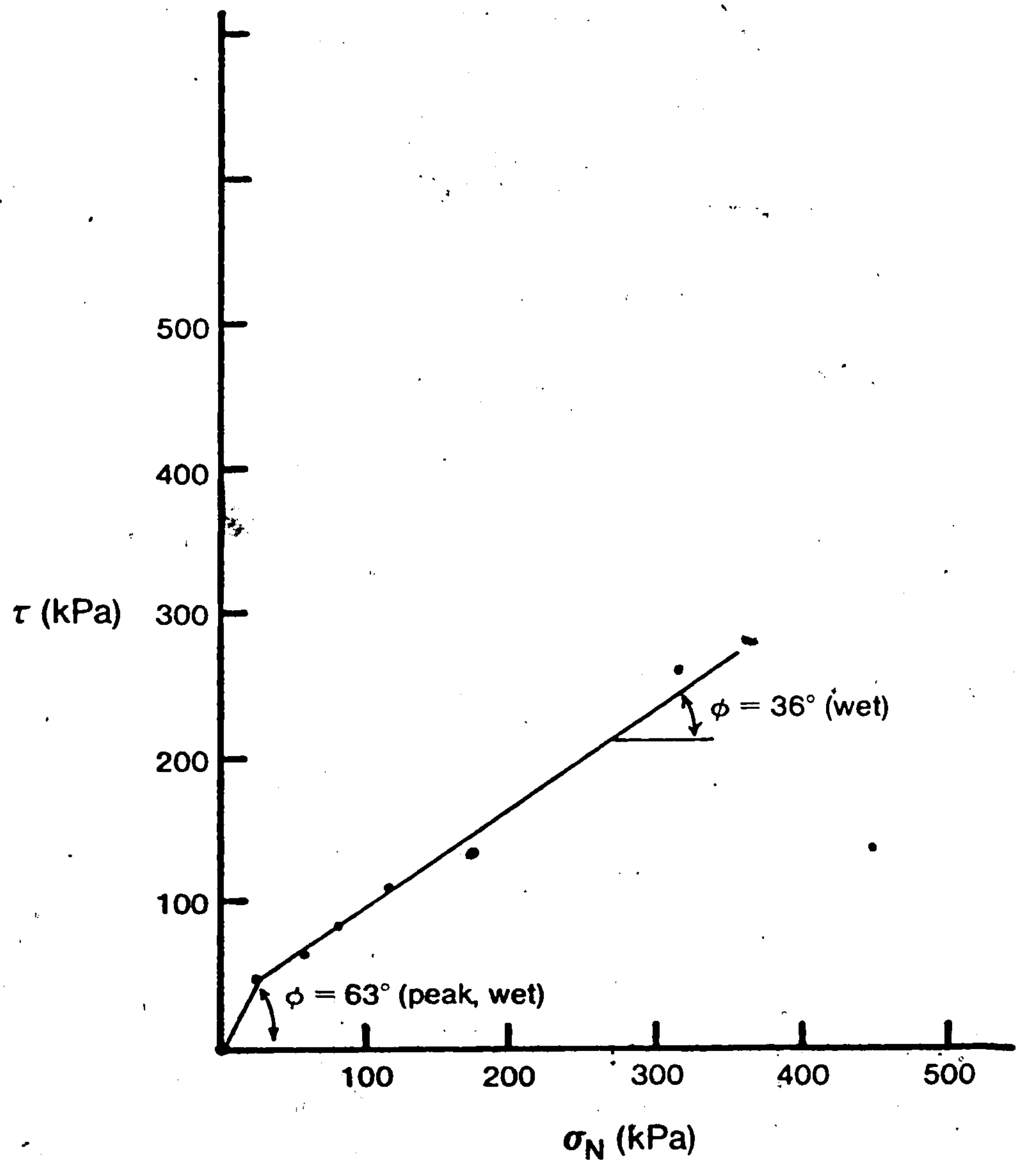


Figure 25g. Shear Strength Versus Normal Stress Along Joint Specimen # 68-2.

Specimen	#23a	#71a	#73
Lithology	Argillaceous Limestone	Very argillaceous limestone	Banded argillaceous and crystalline limestone
Surface Condition		soft & flaky partings w=2.9%	light grey, agrillaceous and soft laminations 1-2 mm. thick
Area	4000mm²	4416mm²	3930mm²
Range of Normal Stress	75-600	17-294KPa	20-336KPa
No. of tests per sample	21	11	9
φinit. dry φfin. dry φinit. wet	64.5° 36.5/32° 35°	54° 38° 34°	65° 52° 52°
Time Submerged	1 hr.	0.5 hr.	10 hrs

Comments: init.=initial shear angle, fin.=final shear angle.
#73 had a clayey surface but was hard underneath.
#23 and #71a had soft, clayey surfaces.

Figure 26. Table of Bedding Direct Shear Tests. Test Conditions and Results.

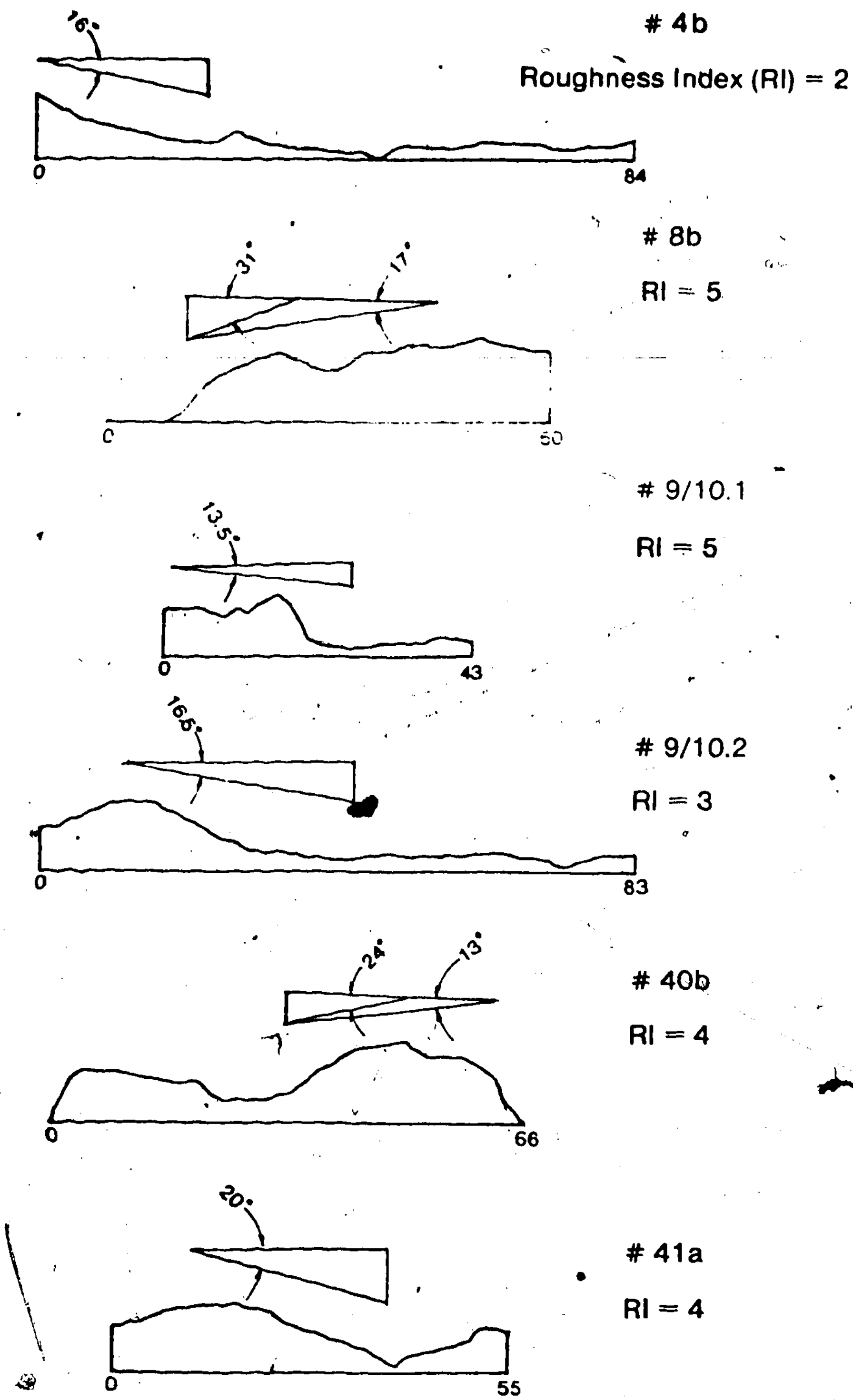


Figure 27. Surface Profiles of Joint Test Specimens.

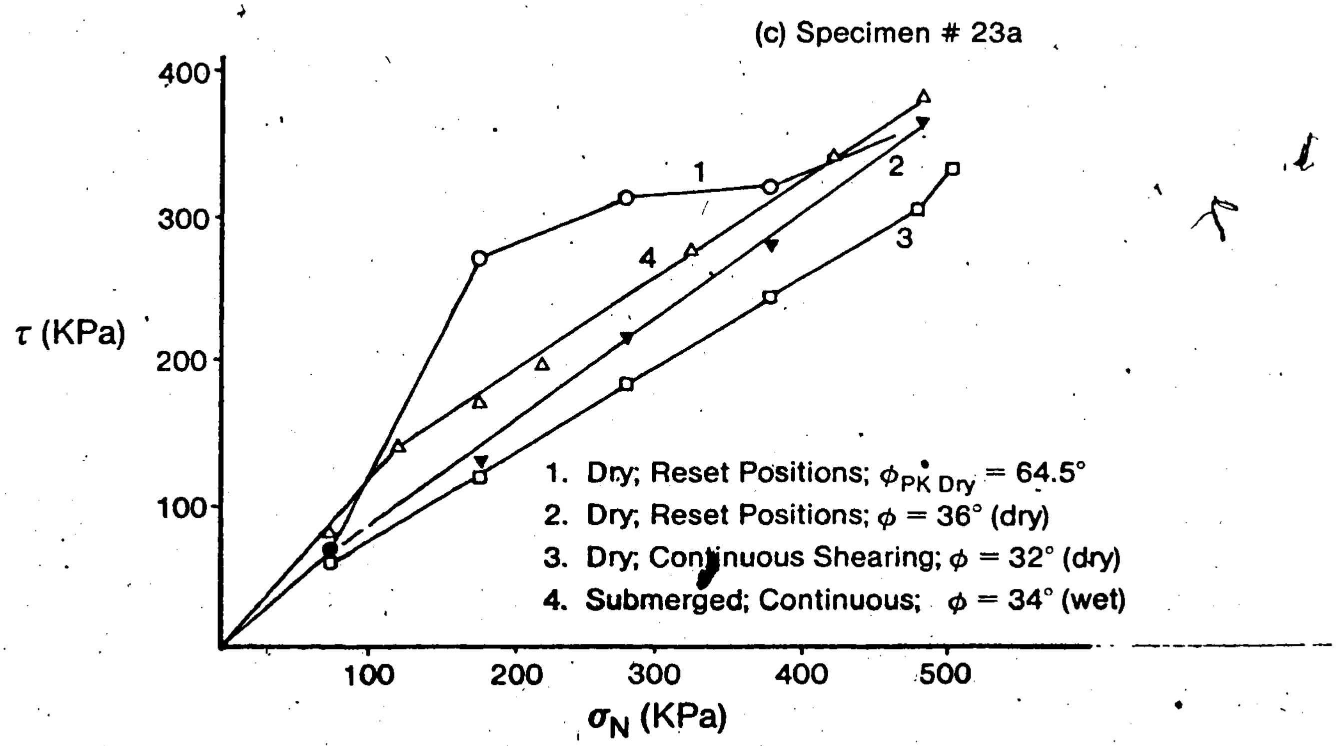
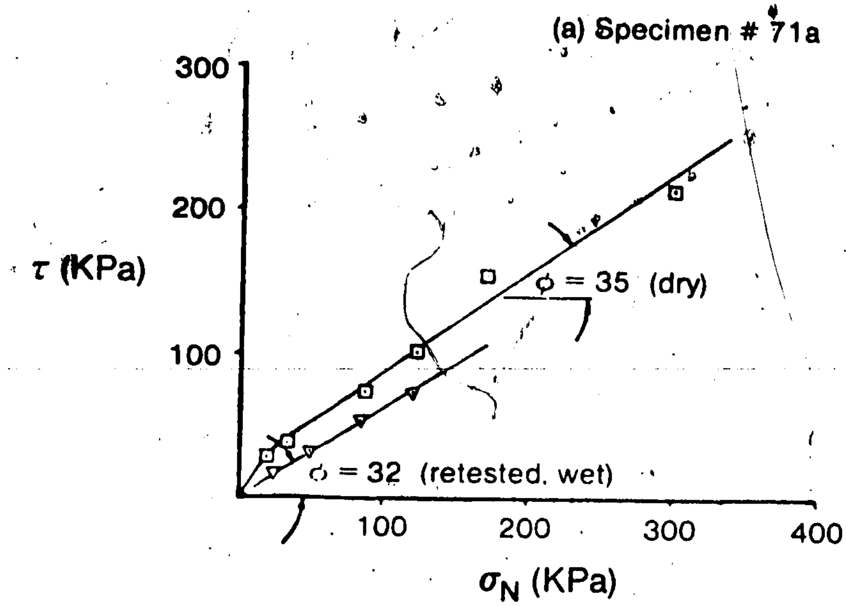


Figure 28. Shear Strength Versus Normal Stress Along Bedding in Specimen # 23a.



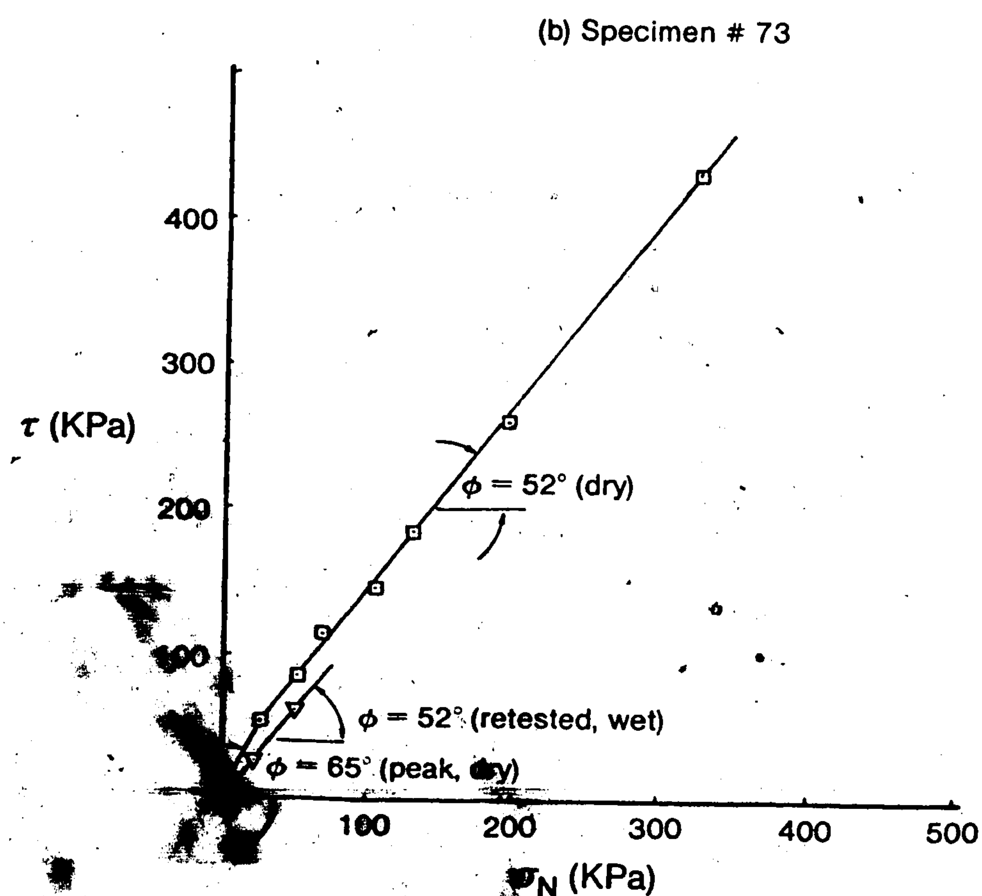


Figure 2_. Shear Strength Versus Normal Stress Along Bedding in Shaly Rocks.

Laboratory Tests		Massive Crystalline Limestone: Biolithic	No Tests	Aphanitic	No Tests	Nodular Limestone: High-Clay Nodular	No Tests	Low-Clay Nodular	No Tests	Shaly Limestone: Disseminated Argil. Micrite	No Tests	Banded Shale /Limestone	No Tests
Clay Content CaCO3 Dissolution		3%	2			3.8%	1	18%	1	26%	1	61%	1
Specific Gravity (Ave+Stan Dev)		2.562±0.047	25	2.521±0.022	4	2.560 ± 0		.031	44	2.535±0.018	35		
Iv, Quick Water Abs. (Porosity)		0.33%(large size) 1.1% (small size)	4 15	0.5%(small size)	1	0.71% (large size) 0.97% (small size)			8 3	1.1%(small size)	10		
Sonic Velocity Ave±SD m/sec.		4730±670	26	5340	1	3500 ± 490			18	2970±310	15		
Hardness: Vickers No/(Scratch)		141±20 / (1 or 2)	18	/ (1)		(1 - 2 for nodules) (3 - 4 for matrix)				106.5±28(2-3)	29	(2-5)	
Uniaxial Compr. Strength Ave±Stan Dev (MPa)		89.6±34.8(41mmSat) 104 ±33.4(54mmDry) 135 ±17.7(54mmSat) 59.5±22.8(75mmDry)	4 3 9 2	131.7±21.6(32mmDry 140 ± 18.6(41mmDry 106 ± 14 (54mmSat	6 6 9	39.8±1.8(54mmDry) 44.1±3.4(75mmDry)	3 5	75.6 (54mmDry)	1	65.1±1.7(54mmDry) 45.2±8.8(75mmDry)	2 6		
Triaxial Cohesion (est., MPa)		21 MPa (dry)		13.8 MPa (sat),		10 (dry)				11.7 (dry)			
Tensile Strength σt(MPa) Ave ± Stan Dev	Direct Pull	5.75 ± 1.35 ( ) 6.89 ± 2.2 ( )	7 4	5.55 ± 1.76 ( ) 5.92	9 1								
	Brazilian	5.97 ± 1.2 (,wet) 3.78 ± 2.7 (,wet)	8 2	3.35 (,wet)	1	3.65±1.3 (dry) 3.48±0.9 (wet)			7 20	4.31±1.1(dry) 2.85±1.2(wet)	13 6		
	Four Point Bending			15.3 ± 0.3 ( )	3								
Double Shear Cohesion, c (MPa)				17.6±4.4 (bed) 10.6±1.3 (bed)	5 3	15.2±4.7(bed) 8.8±0.6(bed)	4 3						
Modulus of Deformation E (MPa)		53740±13000 (MPa)	2	38050±7350 (MPa)	4	23650	1			11410±1320	2		
Poisson's Ratio		0.28 ± 0.06	2			0.13	1			0.205±0.05	2		
Point Load Indices Tdp5 (MPa)		3.06 ± 0.86	8	2.5	1							2.3±0.6(bed)	
Impact Toughness				7.09	15	5.8 ± 1.7 (low-clay) 5.5 ± 1.7 (med-clay) 6.1 ± 2.6 (v weathered)			9	4.5 ± 0.7	2		
Slake Durability		16.3±15(ext weath)	2			94.5±2.9 (low-clay) 91.4±6.6 (high-clay) 39.7±8.8 (v weathered)			4 4 2	88.9 ± 0	2	70.4±17.3(Banded) 23 (Shale)	4 1
Swelling Ability												1.24% (Banded) 9.0% (Shale) 5.7 KPa (Shale)	1 1 1

Figure 30. Table of Intact Properties of the Major Lithologies of the Waterways Formation

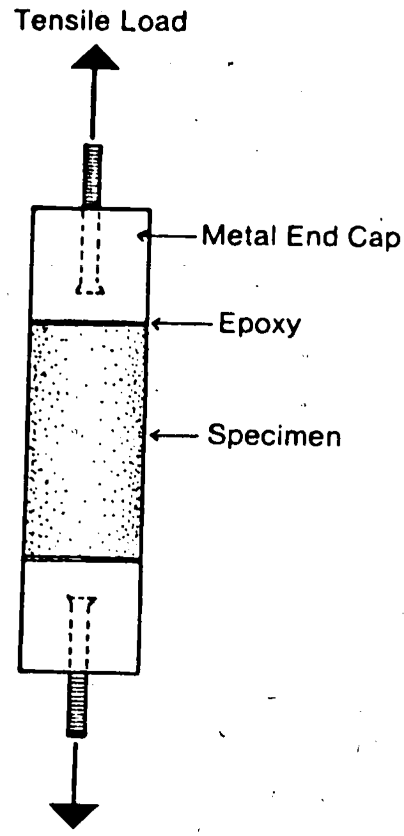
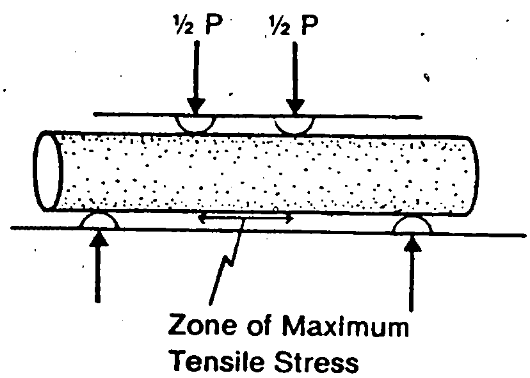


Figure 31. The Direct Pull Tensile Test.



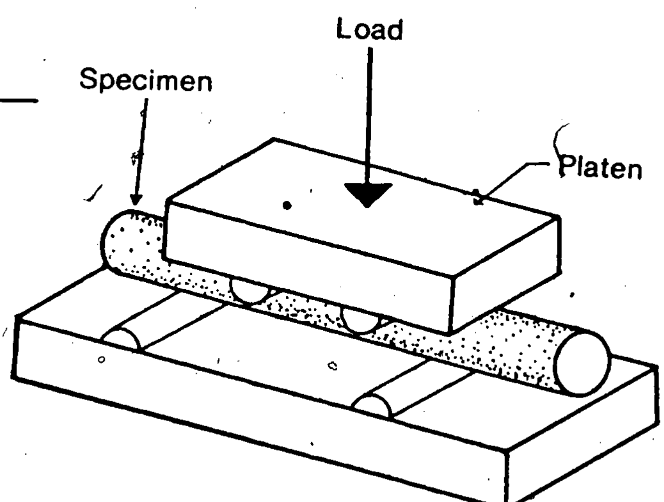


Figure 32. The Four Point Bending Test.

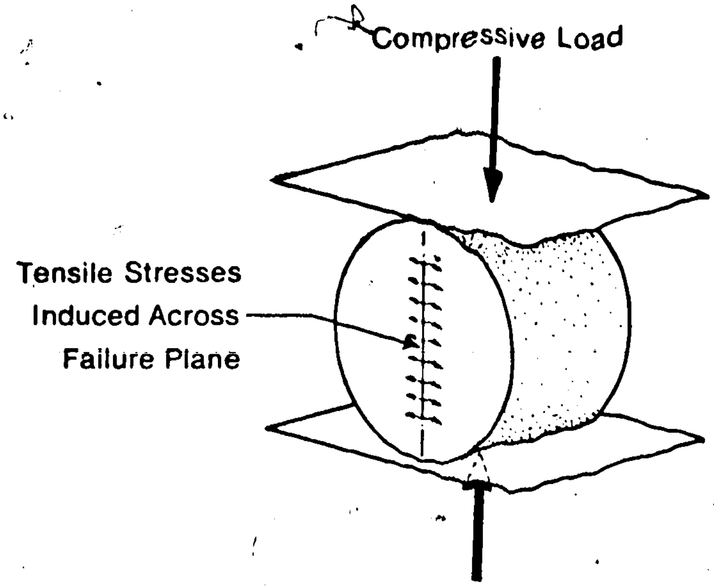


Figure 33. The Brazilian Test Set-Up.

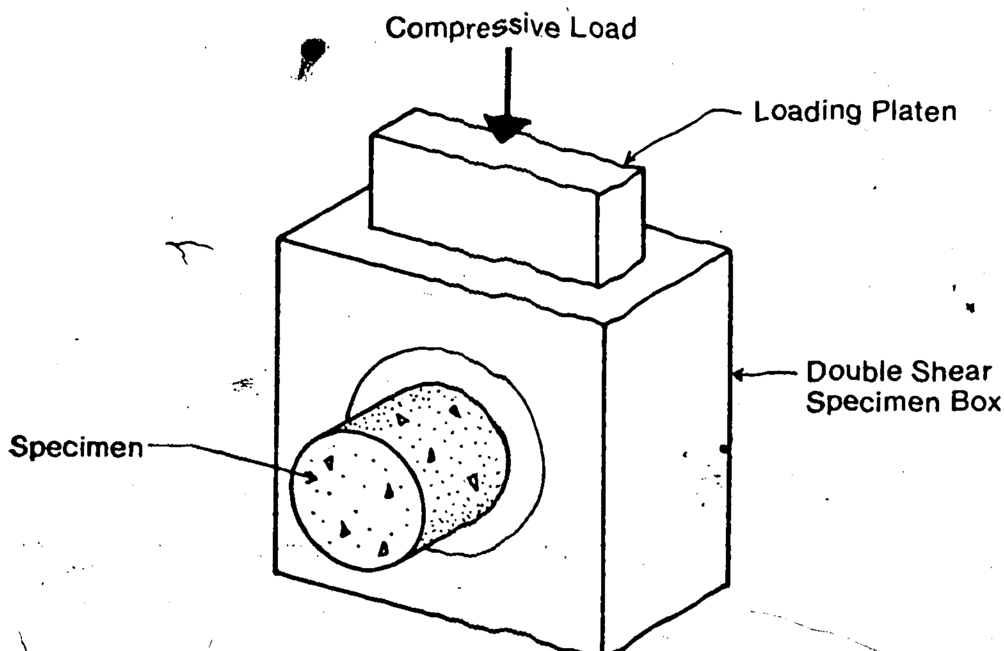


Figure 34. The Double Shear Test.

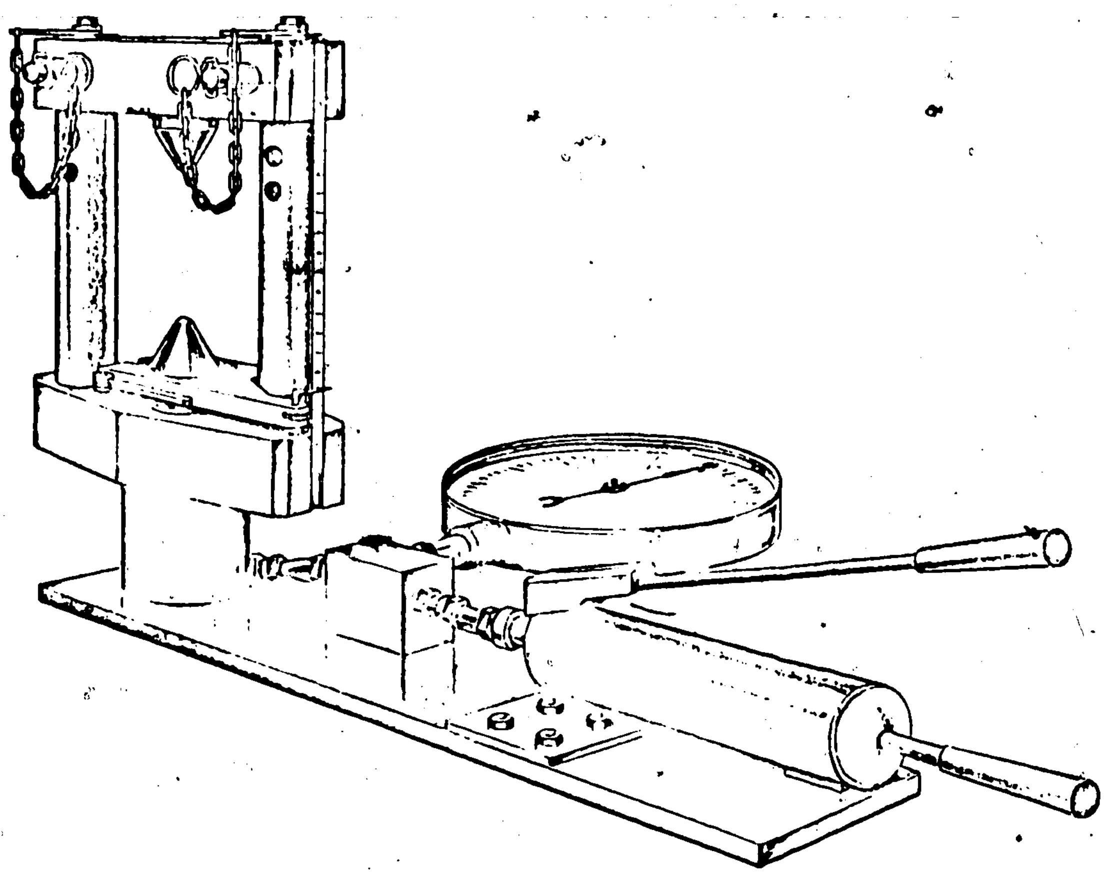


Figure 35. The Point-Load Test Set-Up.
(After Hoek and Bray, 1974)

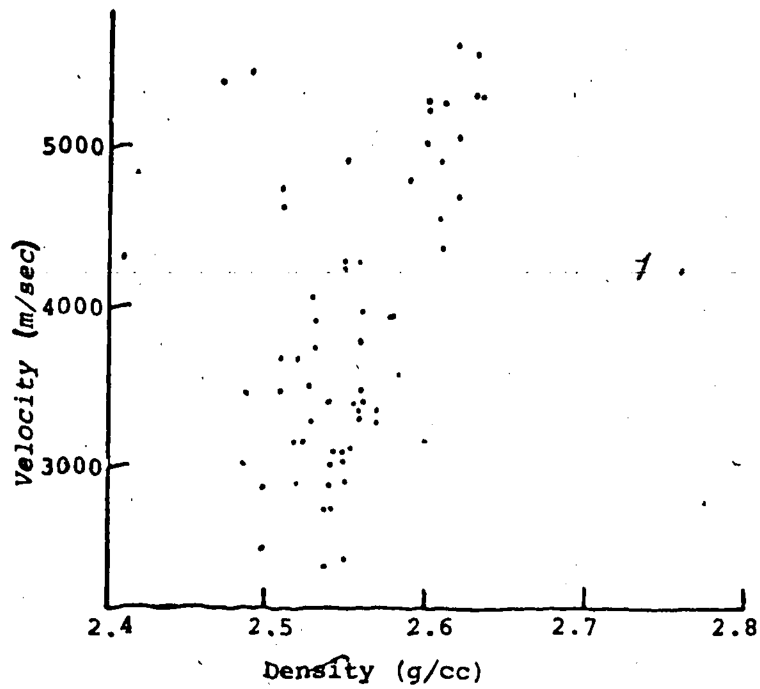


Figure 36a. Ultra Sonic Velocity Versus Density

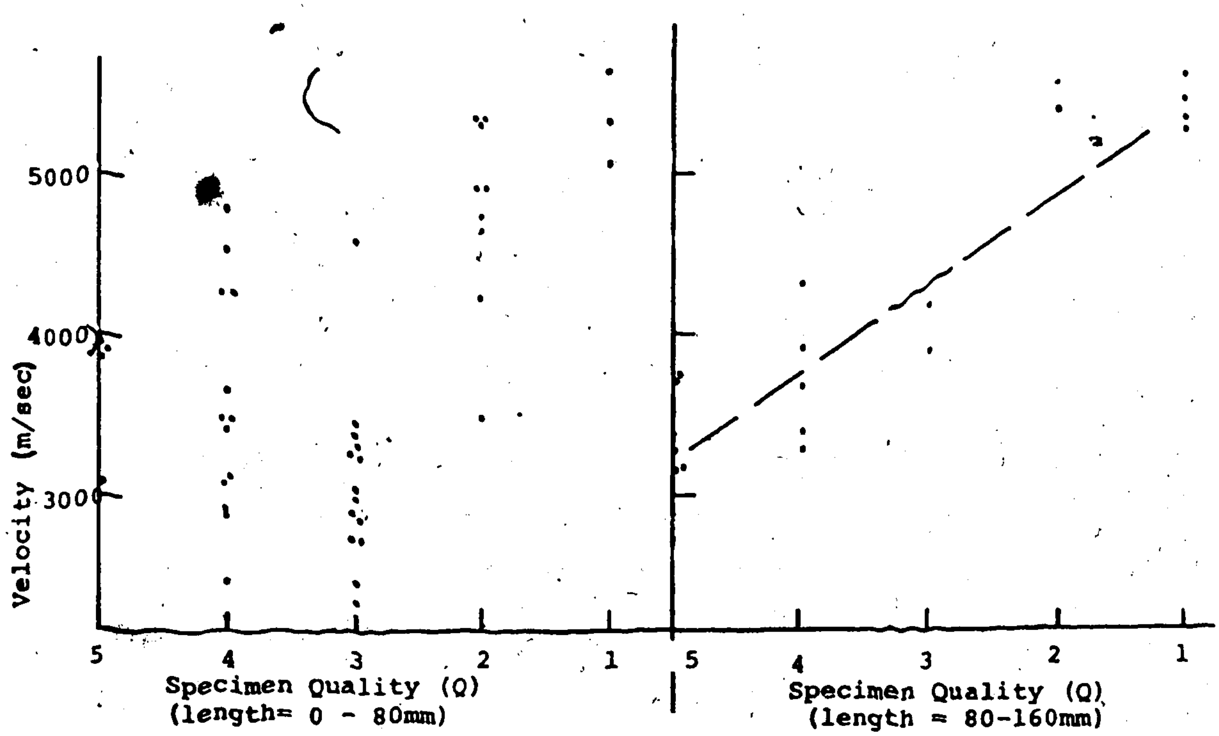


Figure 36b. Ultra Sonic Velocity Versus Quality

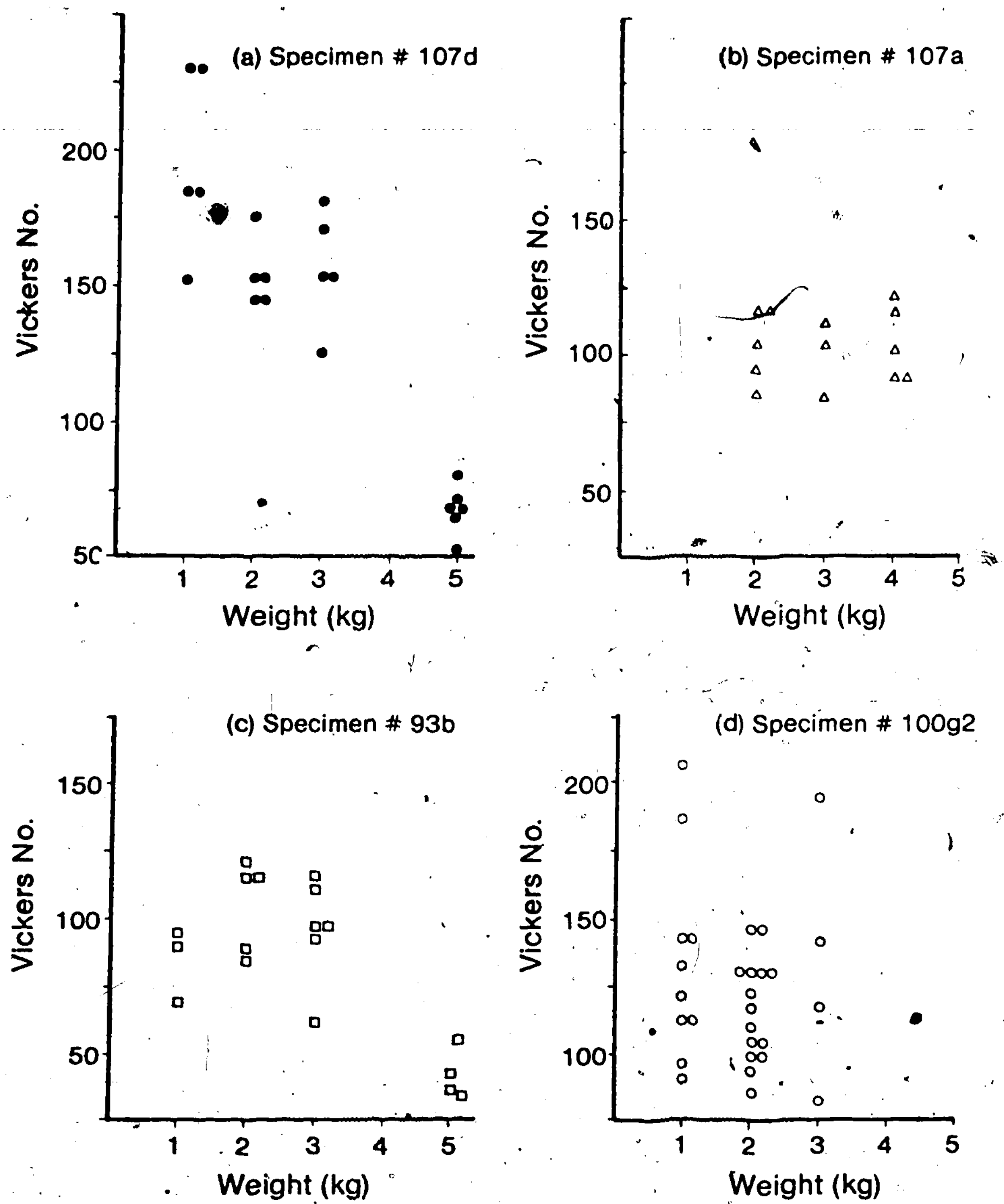


Figure 37. Vickers Hardness. Values of Vickers Hardness Versus Weight Used in Tests on Limestone.

Sample	Lithology	Scratch Hardness	Vickers Hardness (Ave-Stand Dev.)	No. of Trials
107a	Biolithic	2	126 - 13	8
107d	Biolithic	1	156 - 16.5	10
93b	Disseminated Micrite	3	99 - 18.1	11
100g2	Disseminated Micrite	3	114 - 19.7	18
Standard Soft Brass	-	1	144	from Manual

Figure 38. Table Comparing Results of Vickers and Scratch Hardness.

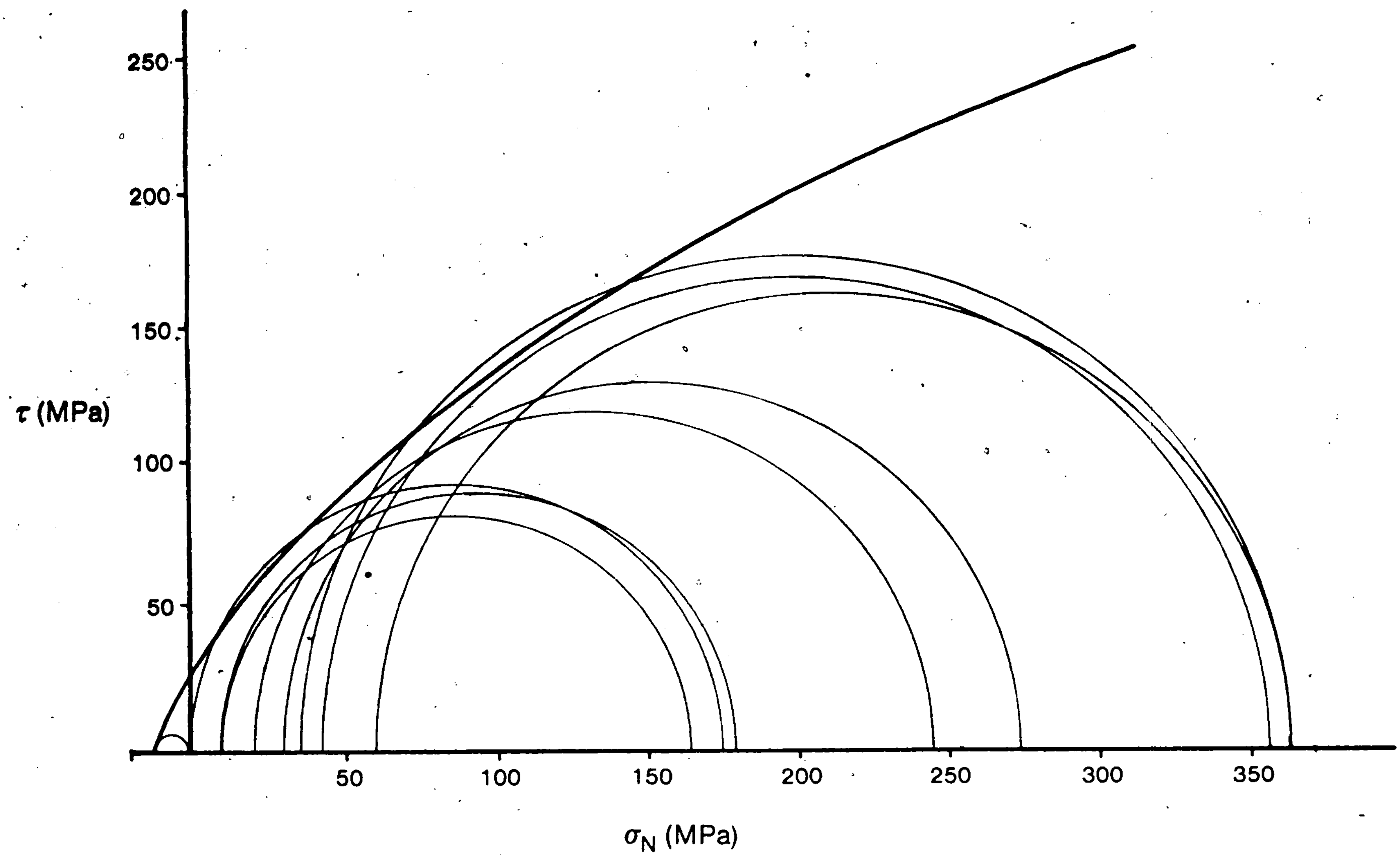


Figure 39. Mohr Envelope for Intact Biolithic Limestone.

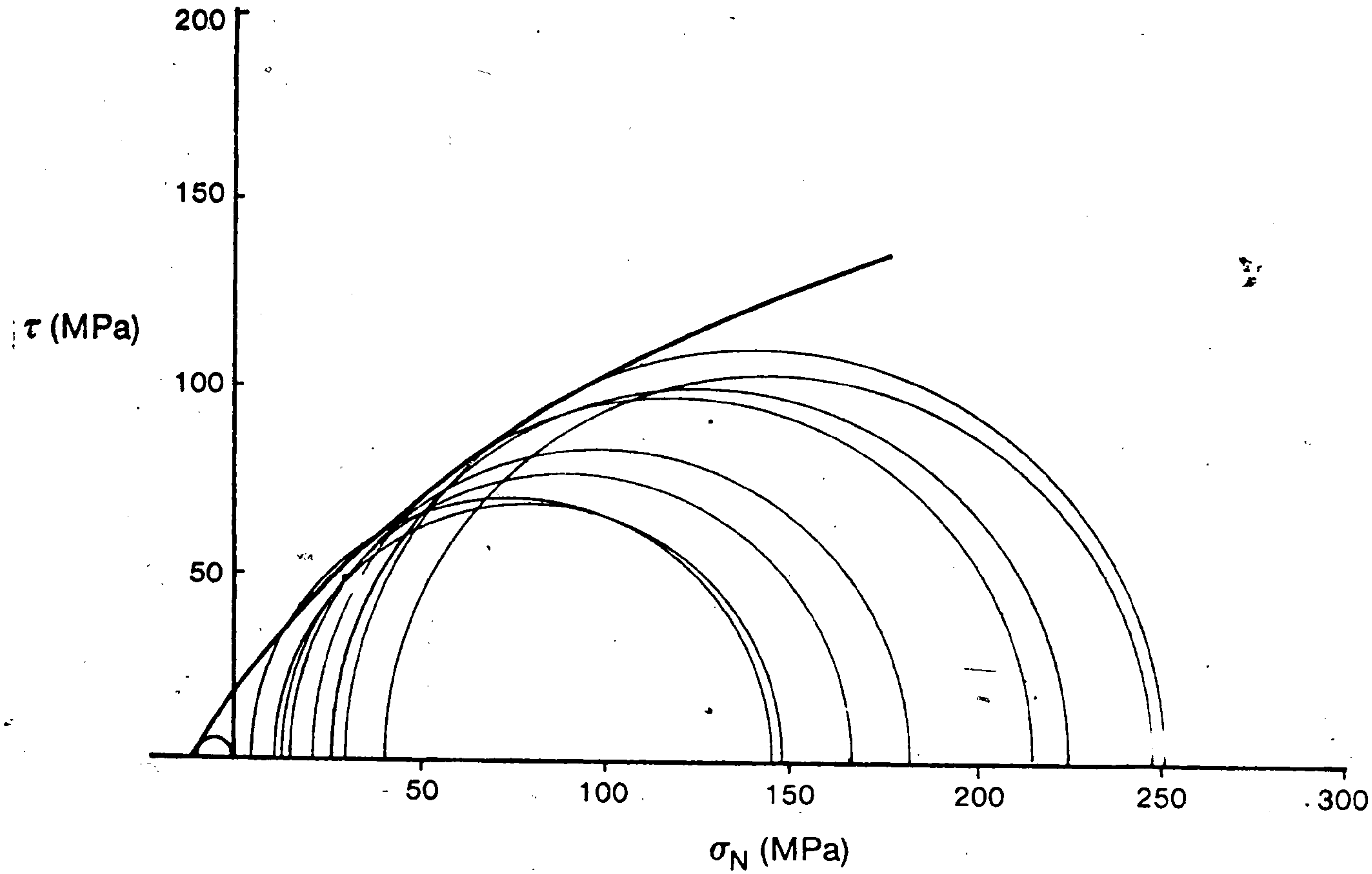


Figure 40. Mohr Envelope for Intact Aphanitic Limestone

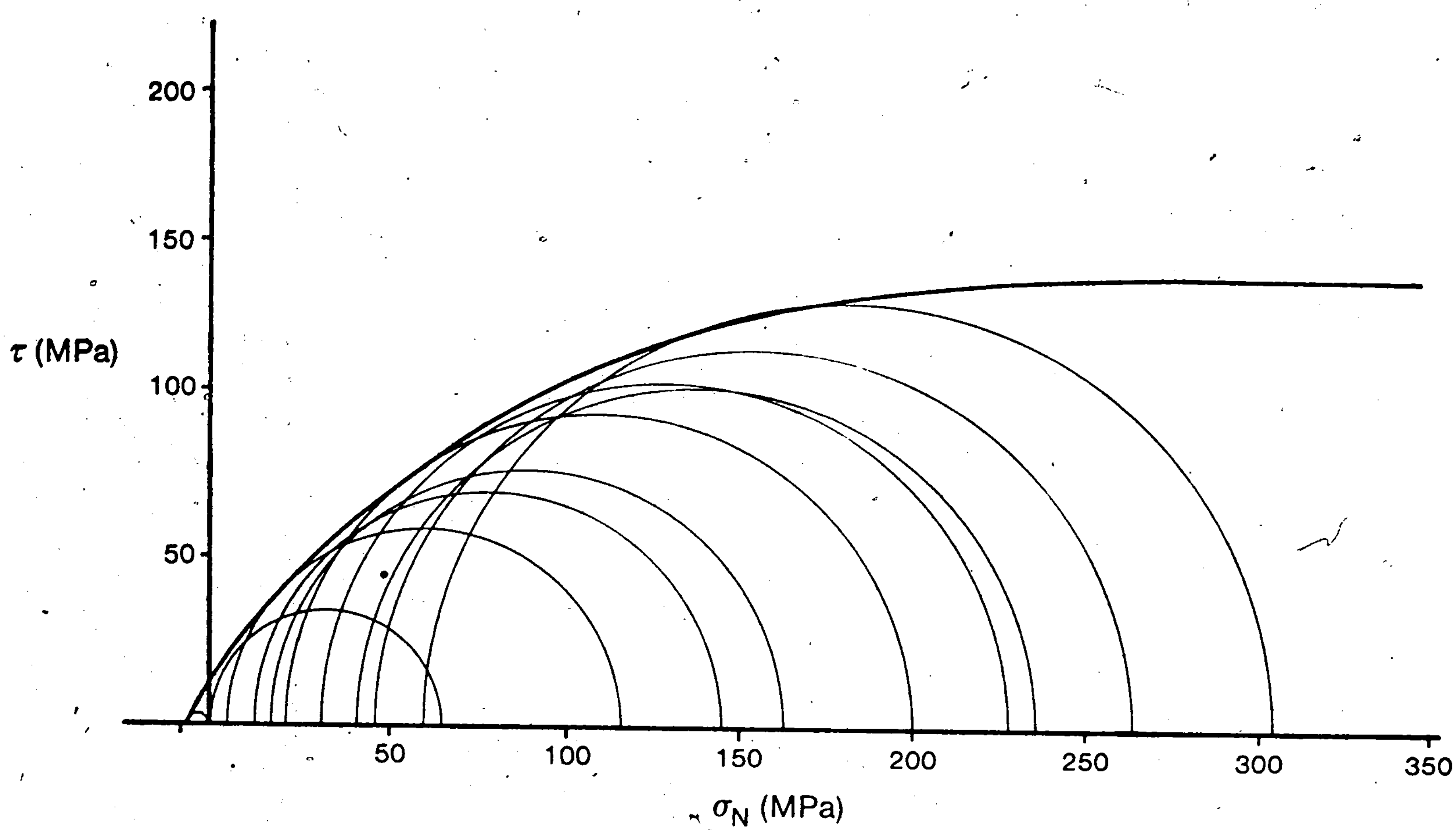


Figure 41. Mohr Envelope for Intact Disseminated Argillaceous Micrite.

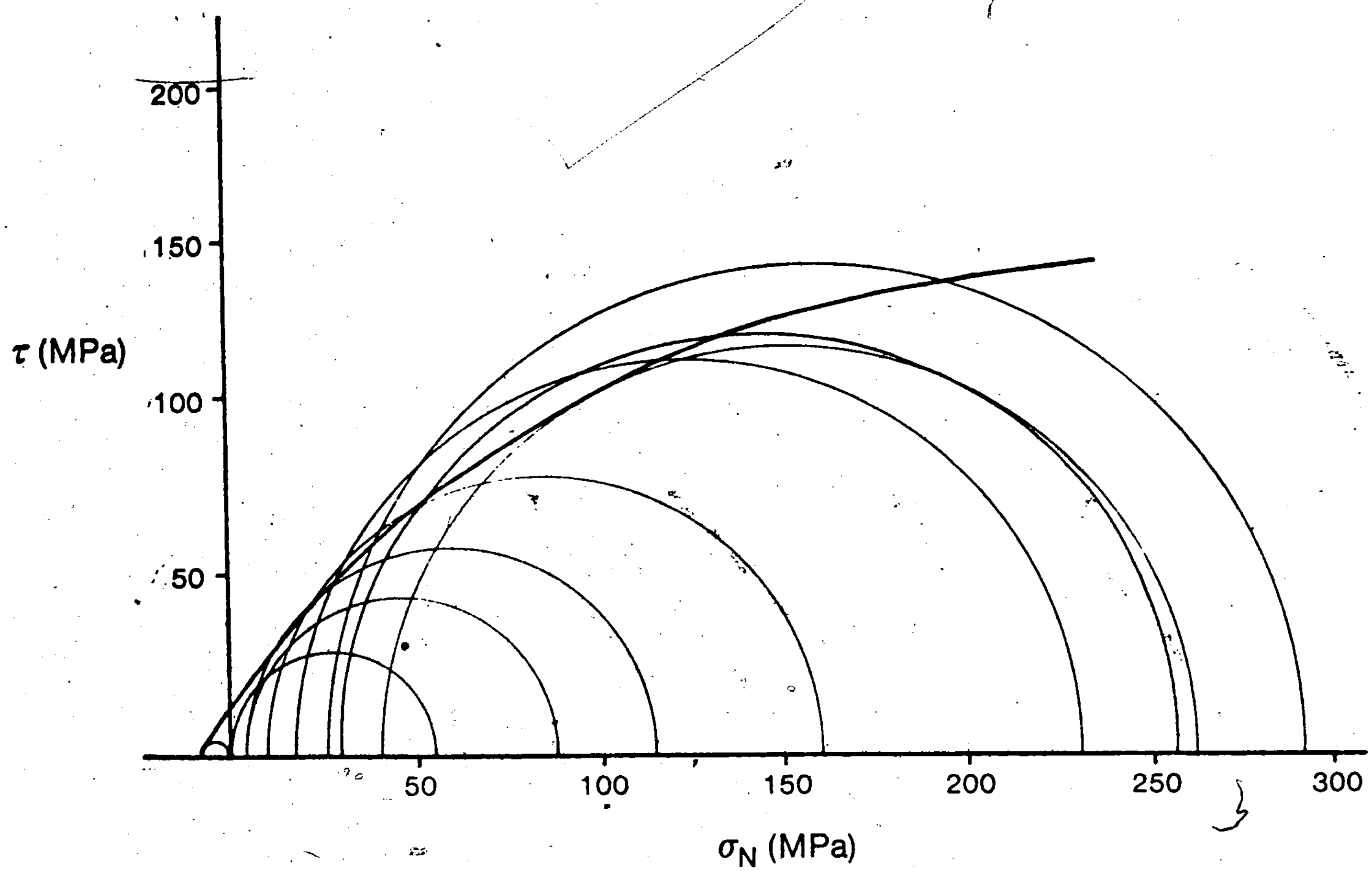


Figure 42 . Mohr Envelope for Intact Nodular Limestone.

Lithology	Method	Young's Modulus (E in MPa)	No of Tests	Poisson's Ratio	No of Tests
Biolithic	Electrical Resistance Strain Gauge- @initial loading	53740 (7.8x10 psi)	2	0.28	2
Aphanitic	Dial Gauge on Platens	38050 (5.5x10	4	+	
Disseminated Argillaceous Micrite	Strain Gauge @50% ultimate load	11,410 (1.7x10 psi)	2	0.14	2
Nodular (medium-clay)	Strain Gauge Initial loading	23,650 (3.4 x 10 psi)	1	0.13	1

Figure 43. Table Summarizing Values of Elastic Moduli of Waterways Formation.

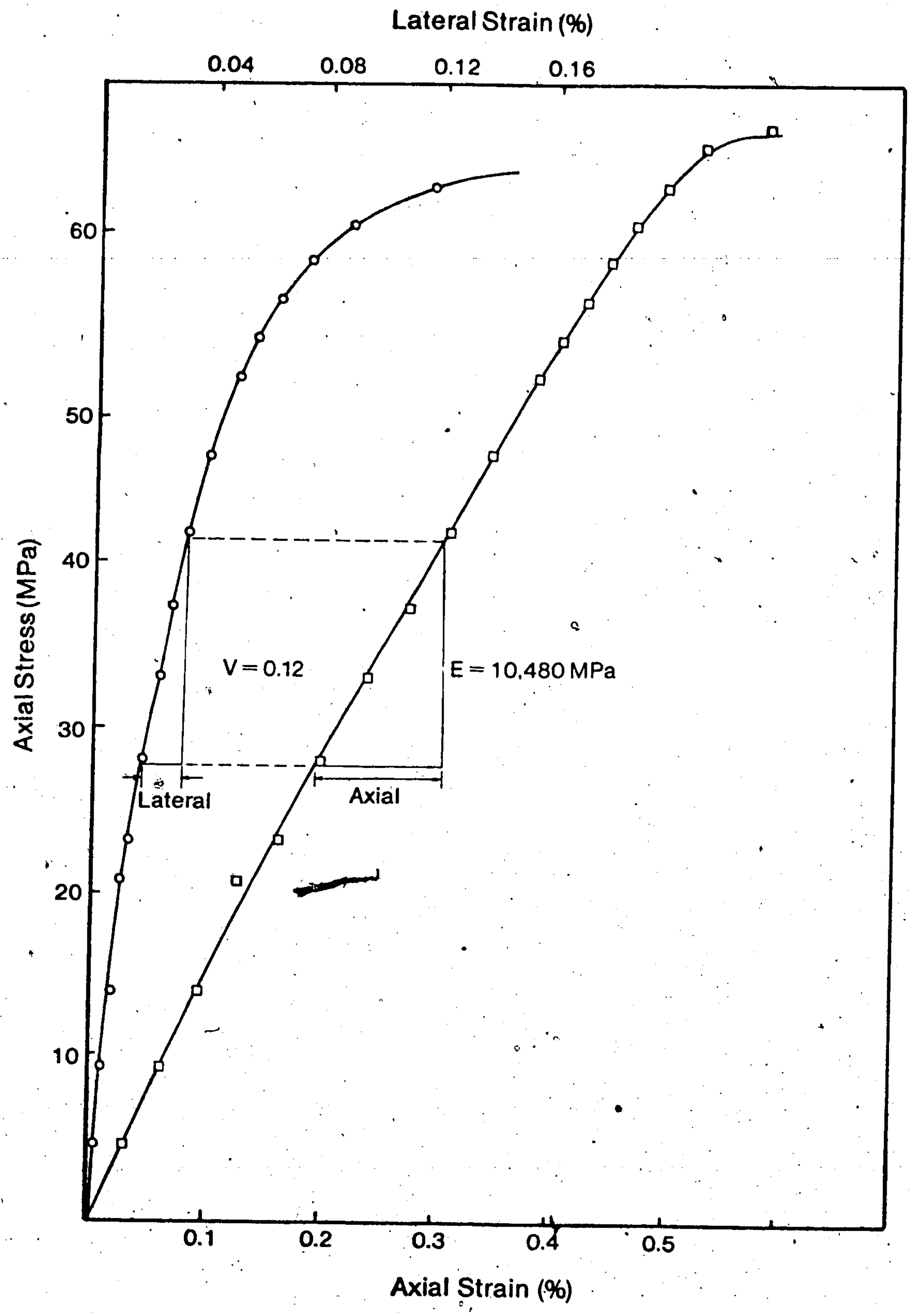


Figure 44a. Axial and Lateral Strains During Uniaxial Compression of Specimen # 98B

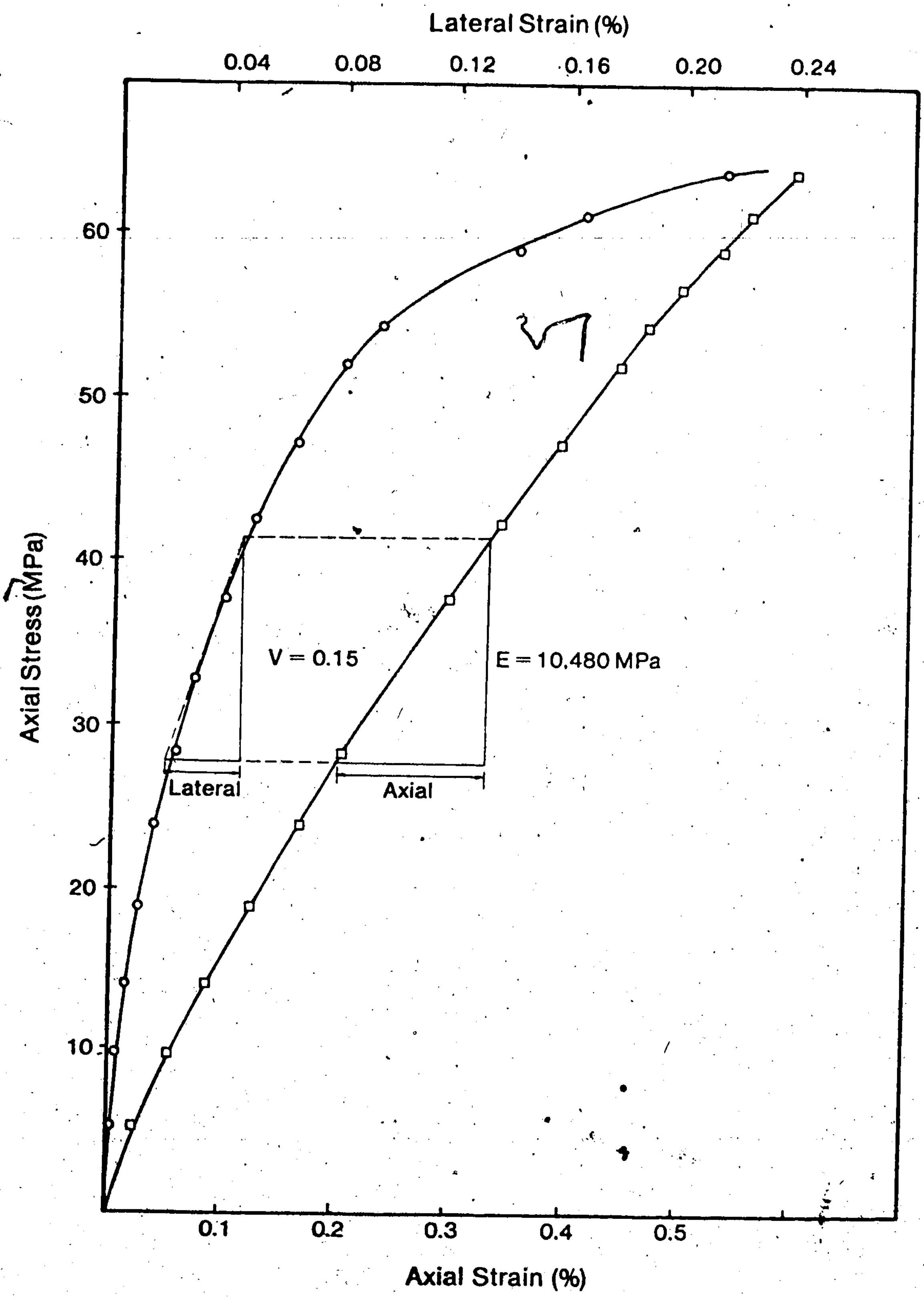


Figure 44b. Axial and Lateral Strains During Uniaxial Compression of Specimen #100f.

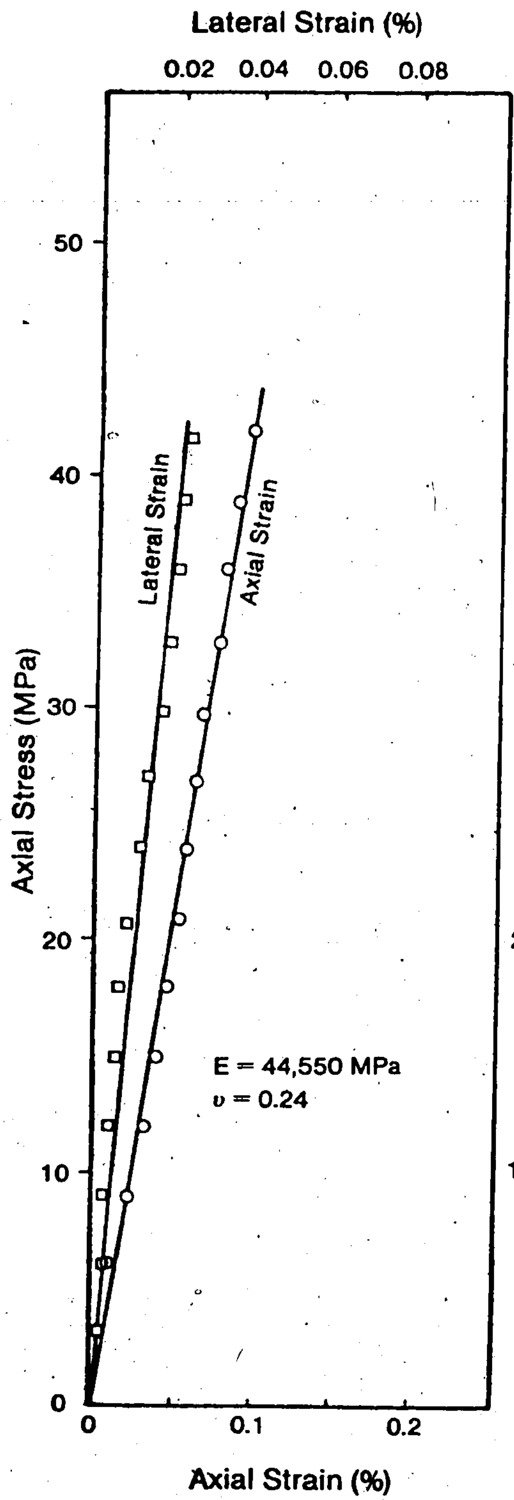


Figure 45. Axial and Lateral Strains in Specimen # 49a (Massive).

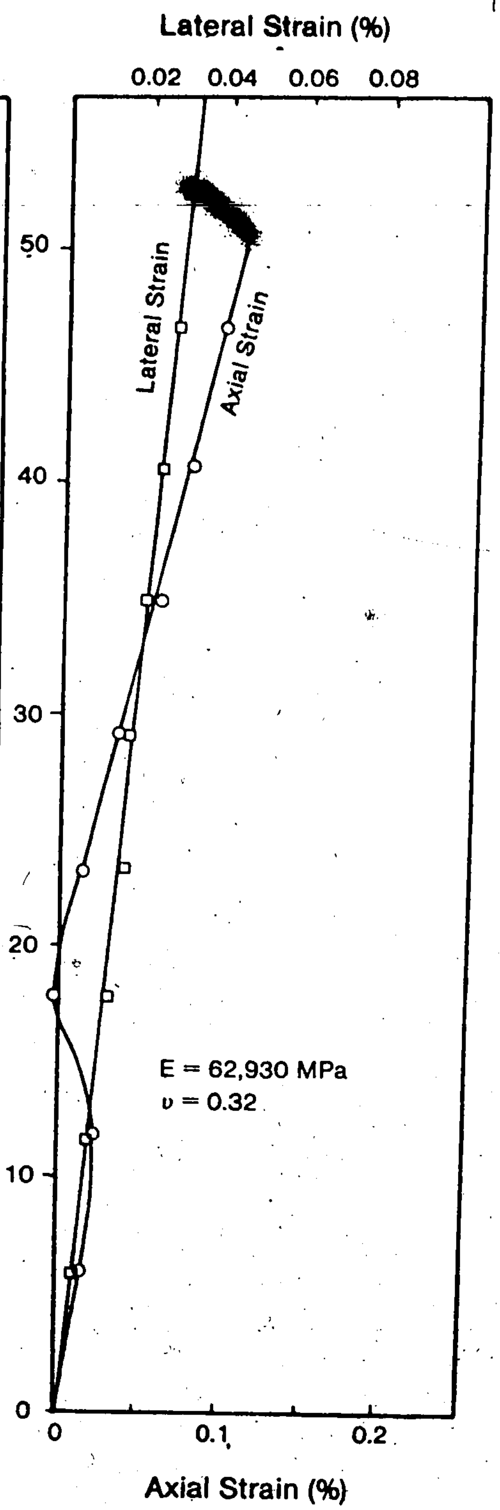


Figure 46. Axial and Lateral Strains in Specimen # 45b (Massive).

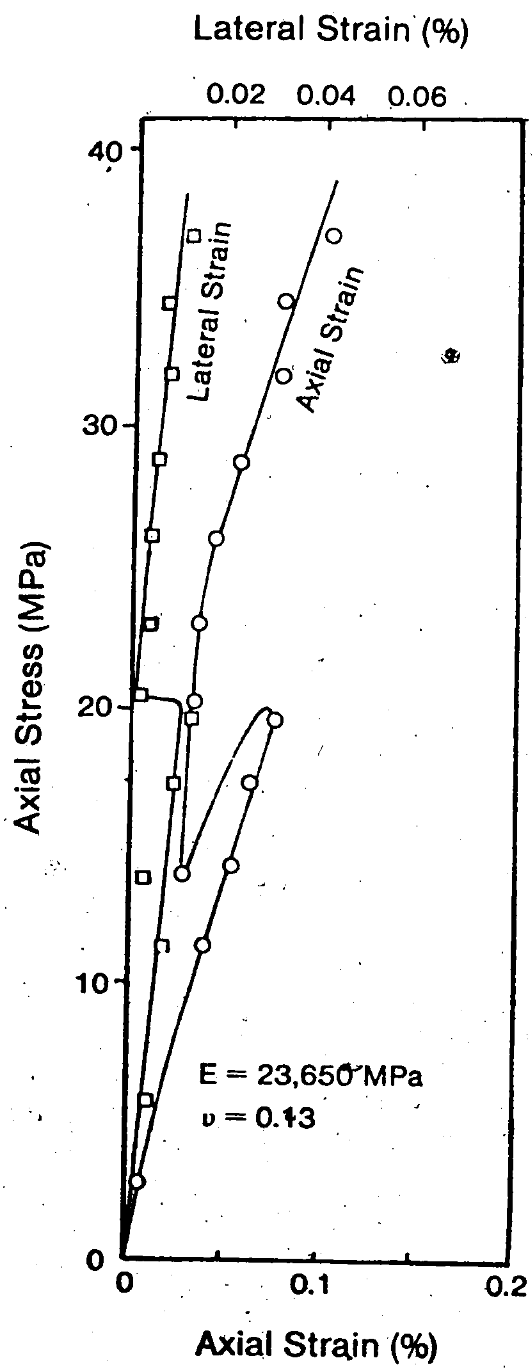


Figure 47. Axial and Lateral Strain in Specimen # 82d (Nodular)

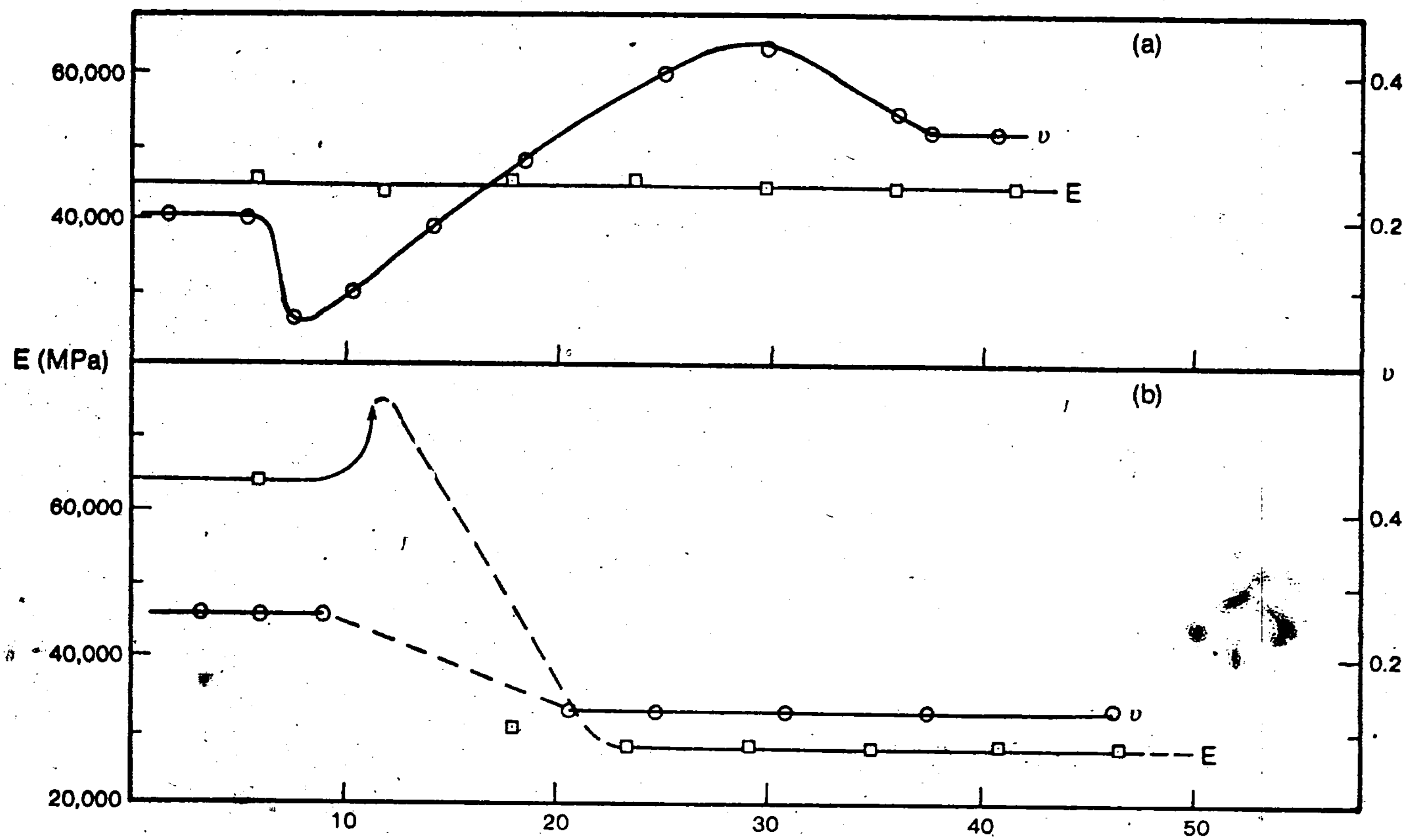


Figure 48. Variation of Elastic Constants With Stress.
Specimens # 49a (a) and 45b (b)

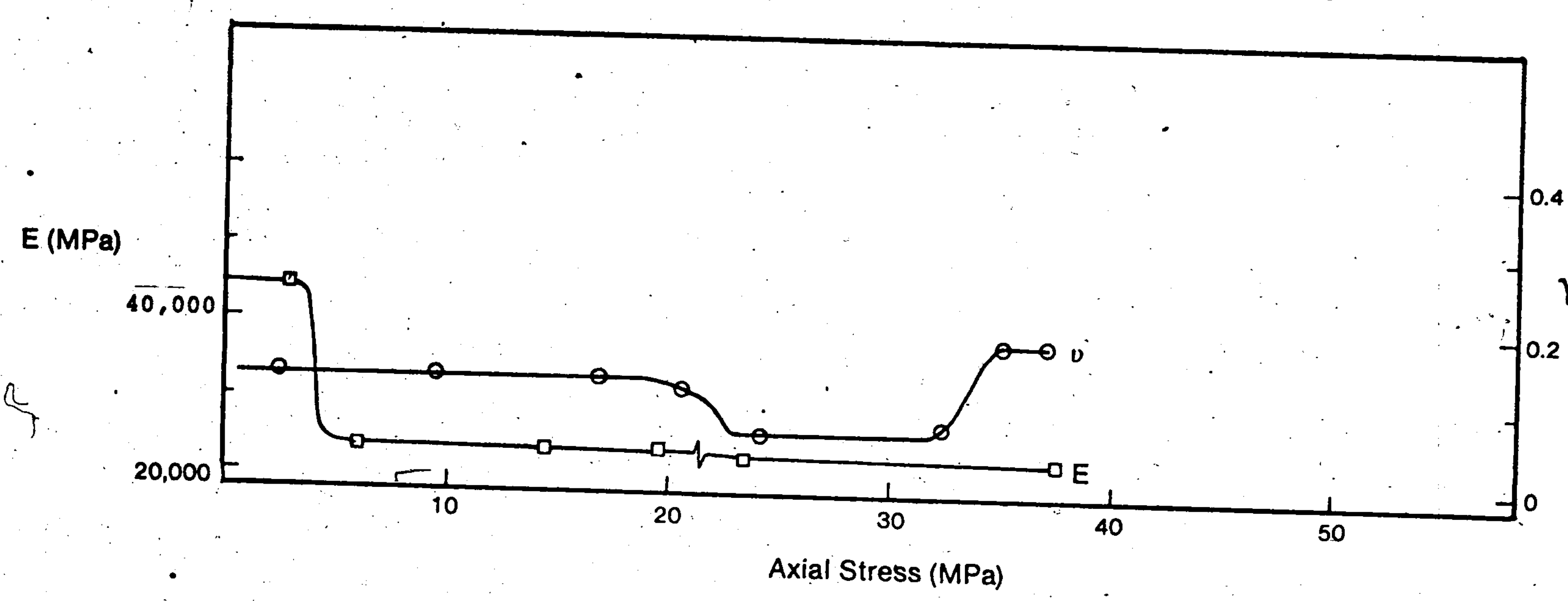


Figure 49. Variation of Elastic Constants With Stress, Specimen no. 82d.

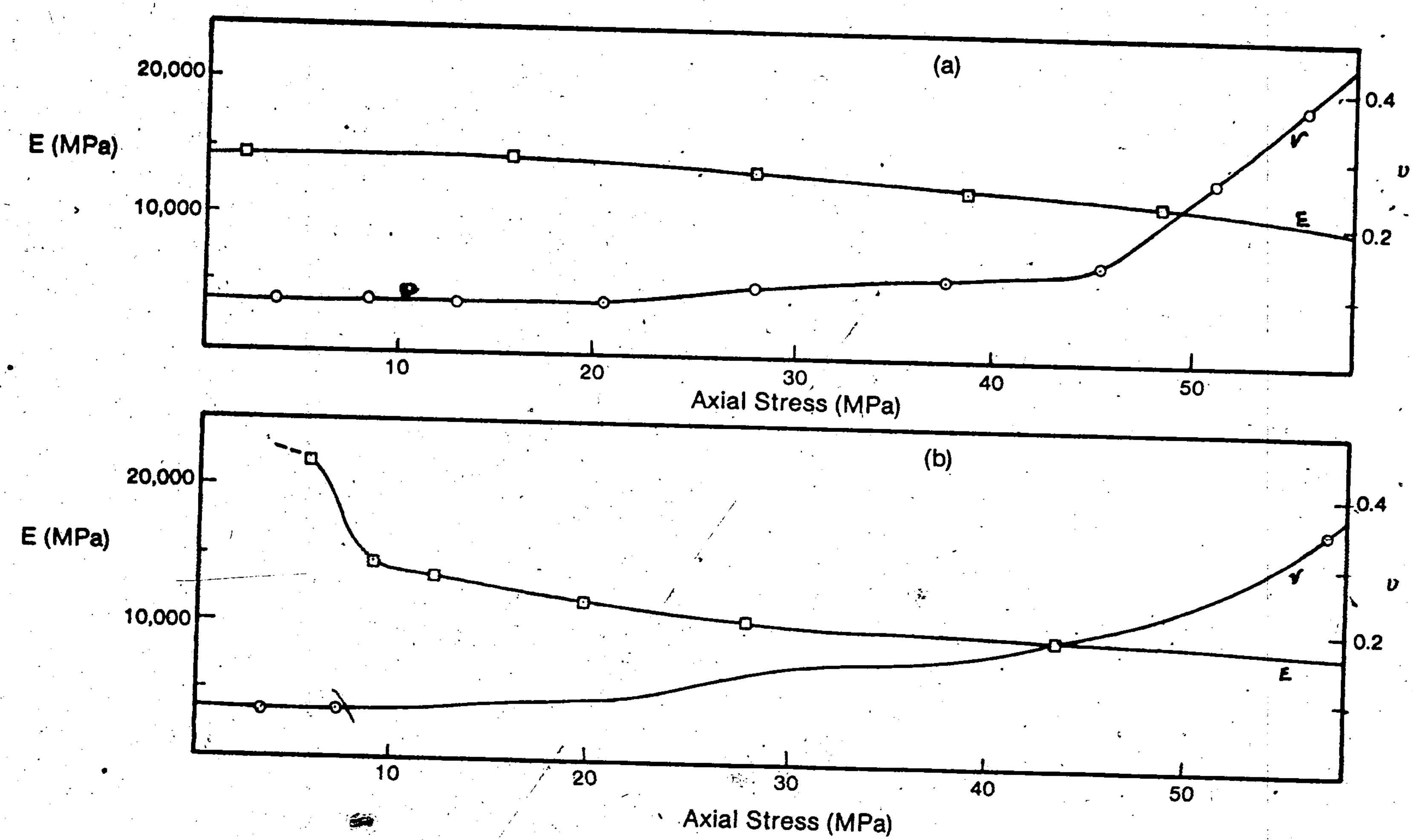


Figure 50. Variation of Elastic Constants With Stress, Specimens # 98b (a) and 100f (b).

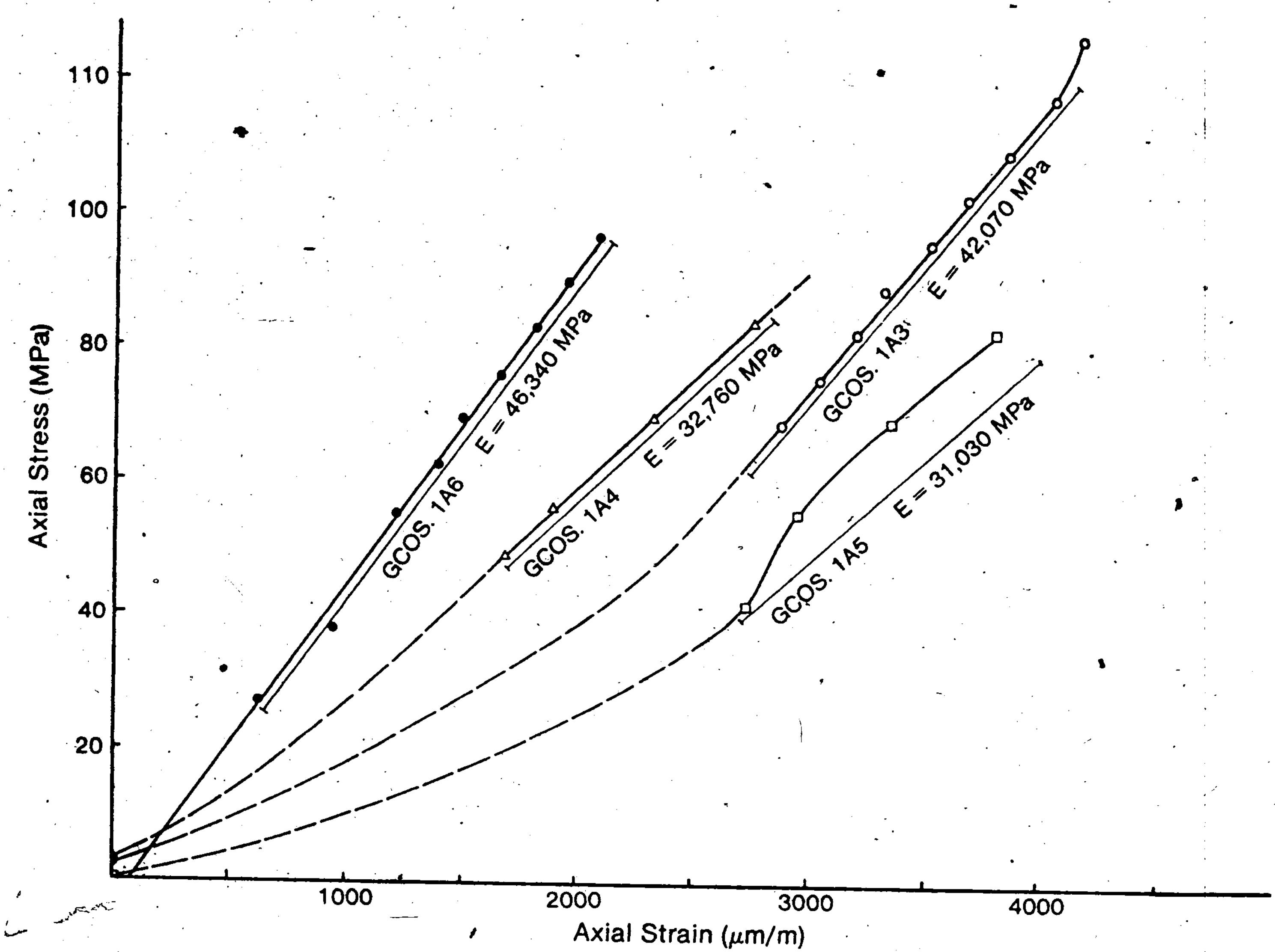


Figure 51. Axial Strain in Uniaxial Compression of Creep Samples

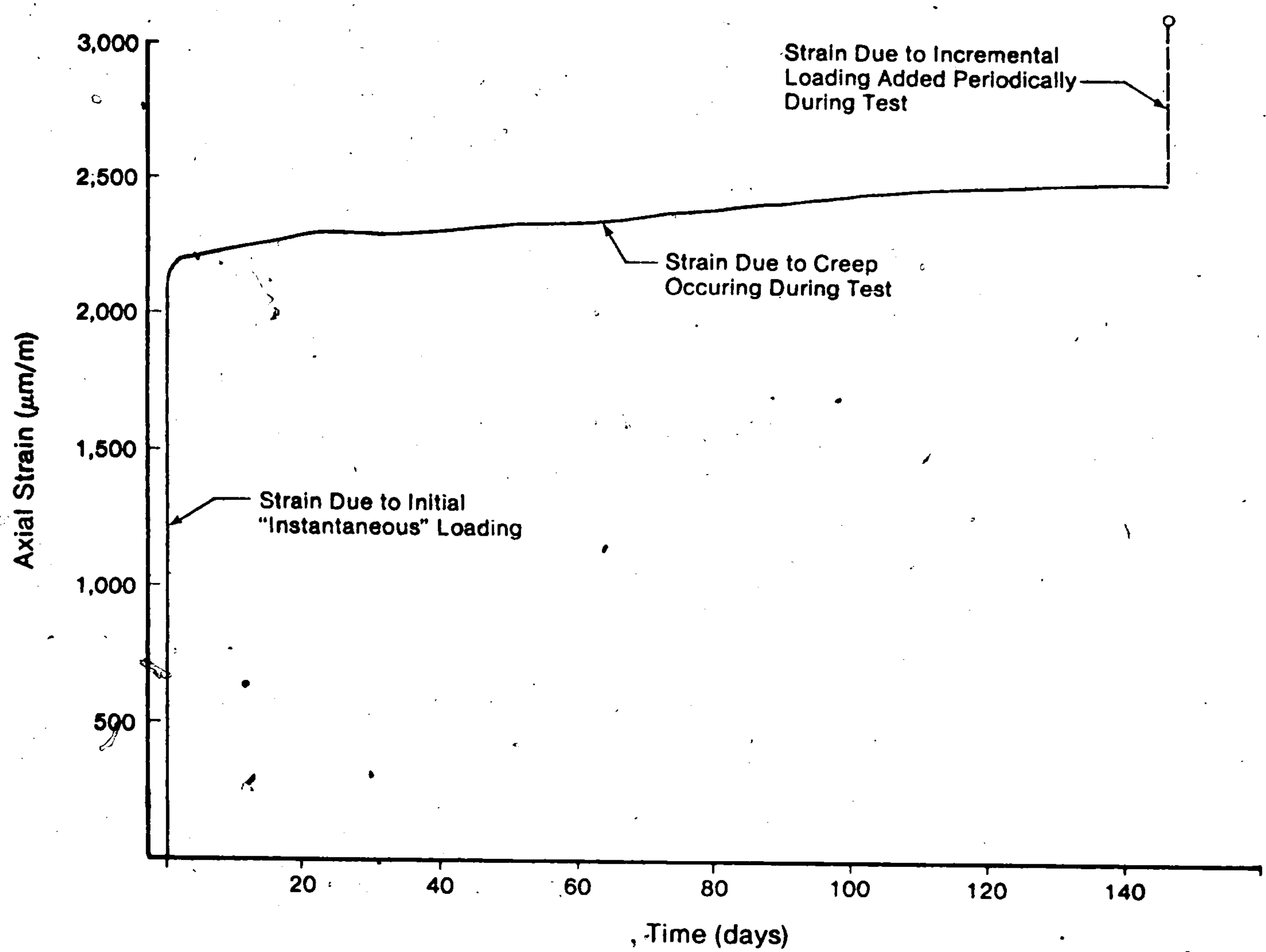


Figure 52. Axial Strain in Creep Sample # GCOS. 1C6.

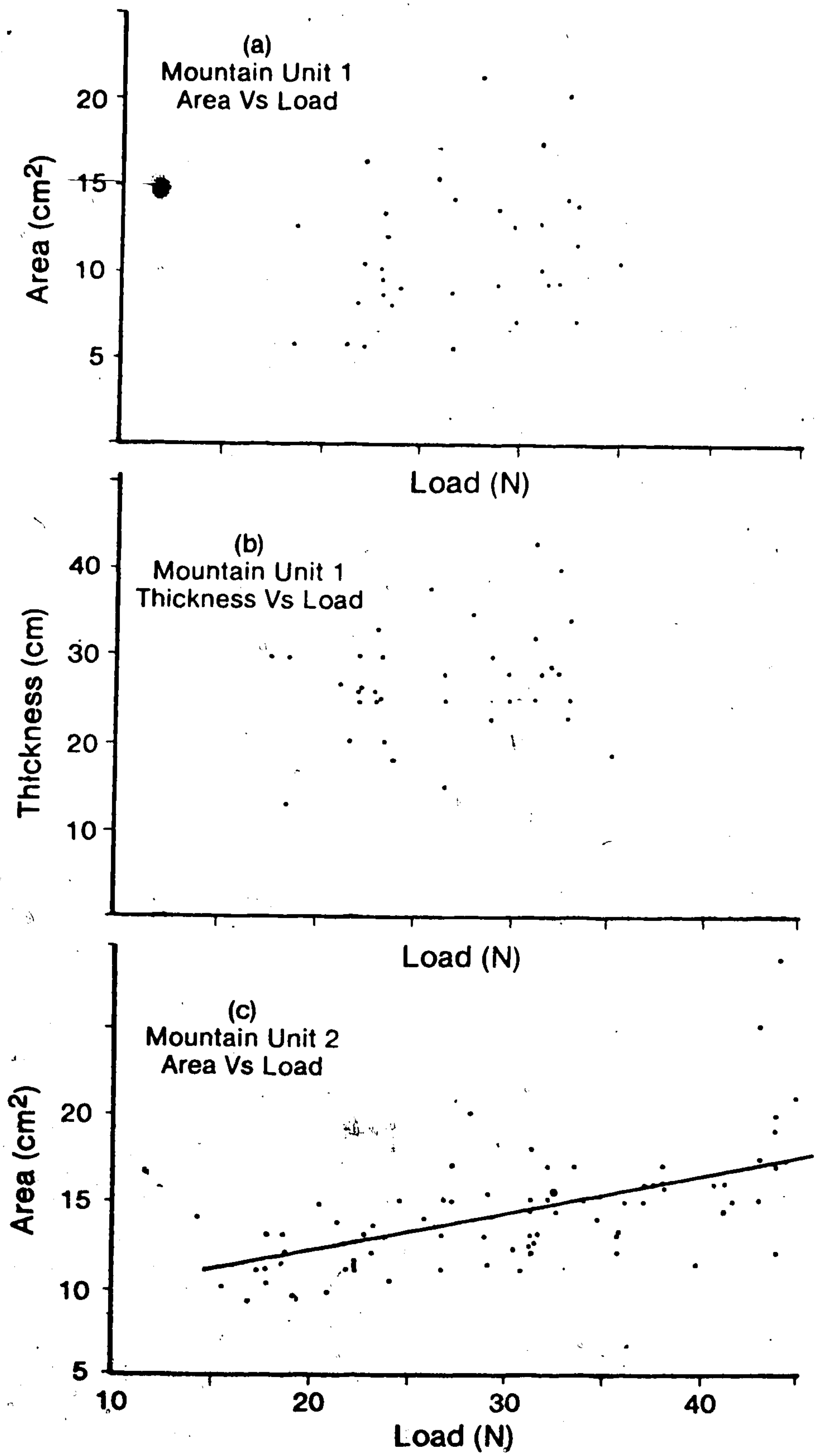


Figure 53. Graphs of Field Point Load Testing

	Sample No. #	Lithology	Isd % (2nd cycle)	Index (%) After (n) cycle
WW1	18	Banded Shaly	70.5	66 (4)
	24a	Banded Shaly	92.0	86 (4)
	33a	Nodular - low-clay	96.0	94 (4)
	56a	Banded Shaly	49.6	36 (4)
	60a	Banded Shaly	69.3	53 (4)
	72	Nodular -	87.8	83 (4)
	77a	Disseminated Argill. Micrite	88.9	84 (4)
	96a	Disseminated Argill. Micrite	88.9	83 (4)
MOUNTAIN	4	Nodular medium clay	96.9	96 (3)
	5	Nodular - medium clay	96.9	96 (3)
	6	Nodular - medium clay	83.9	83 (3)
NumS1154		Biolithic very weathered	26.8	
NumS1155		Biolithic - very weathered	5.7	
Sync1.225		Nodular - very weathered	44.9	
Sync1.227		Nodular - low-clay	90.4	
Sync1.239		Nodular - low-clay	96.7	
Sync2.238		Nodular - very weathered	32.5	
Sync2.242		Shale	23	
Sync2.258		Nodular - low-clay	95	

Figure 54. Table of Slake Durability Indices of Argillaceous Rocks of the Waterways Formation. - Method of Barton (1974).

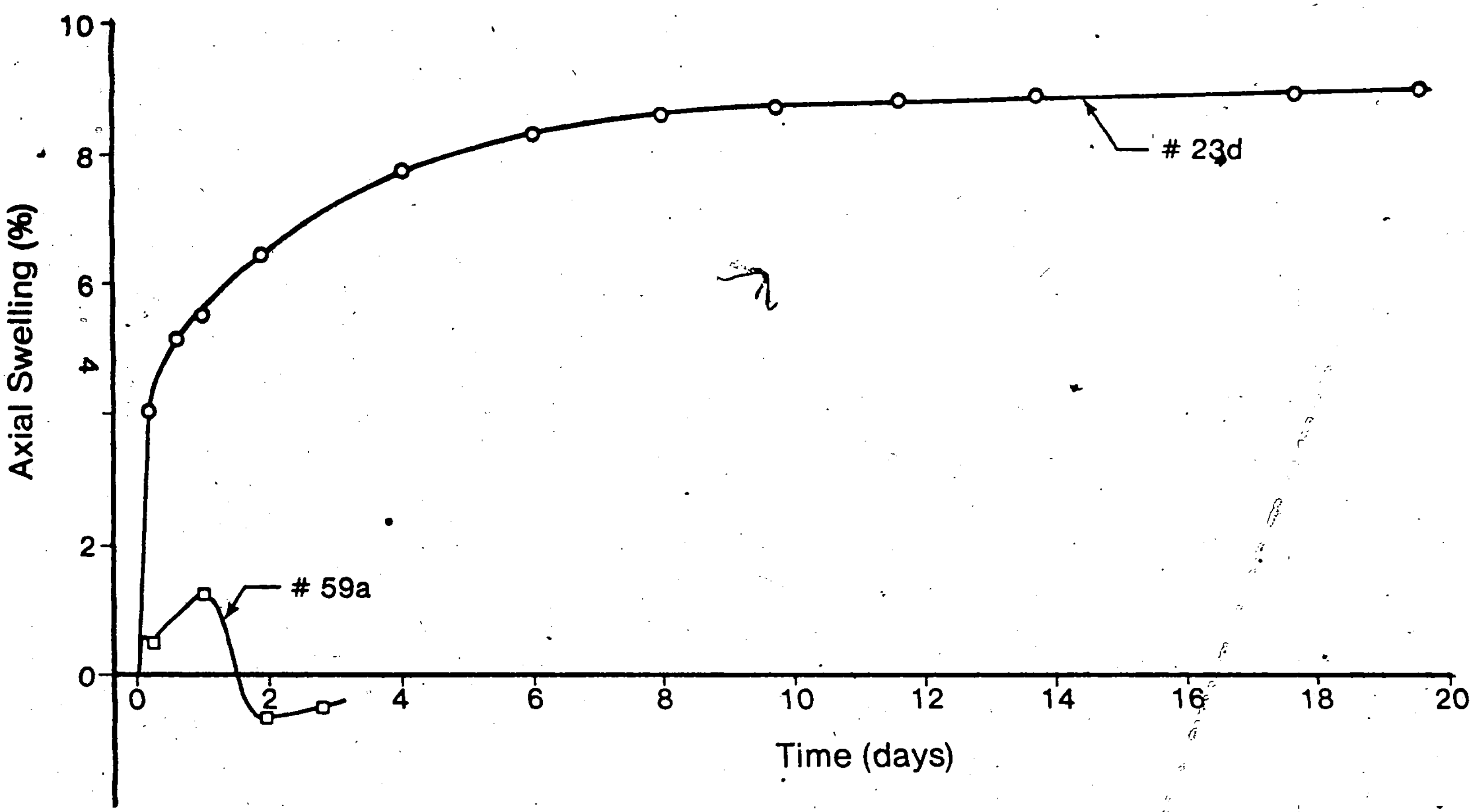


Figure 55. Free Swelling Tests in Shaly Rocks.
Graph of Axial Strain Versus Time.

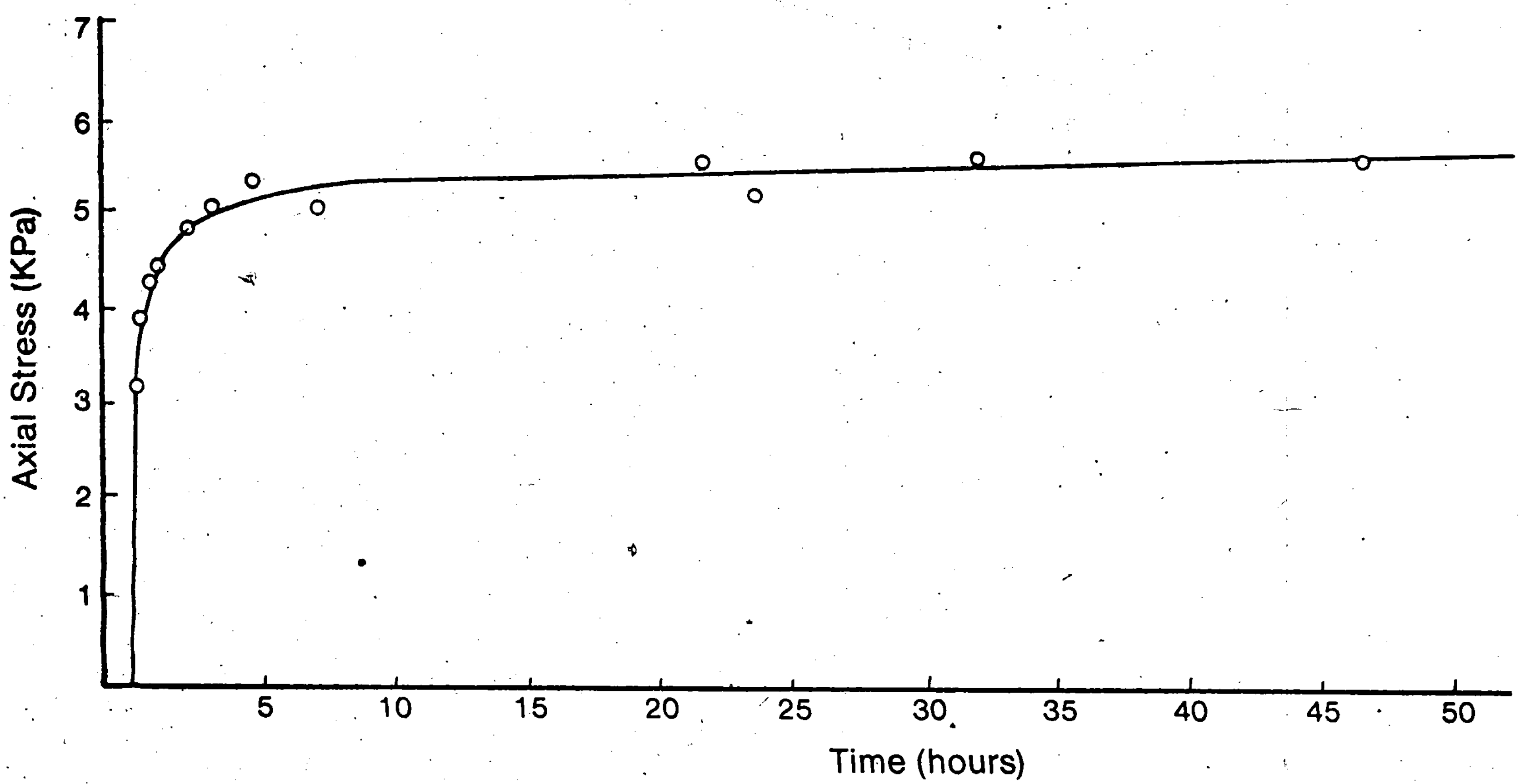


Figure 56. Confined Swelling Test in Shale.
Graph of Pressure Versus Time

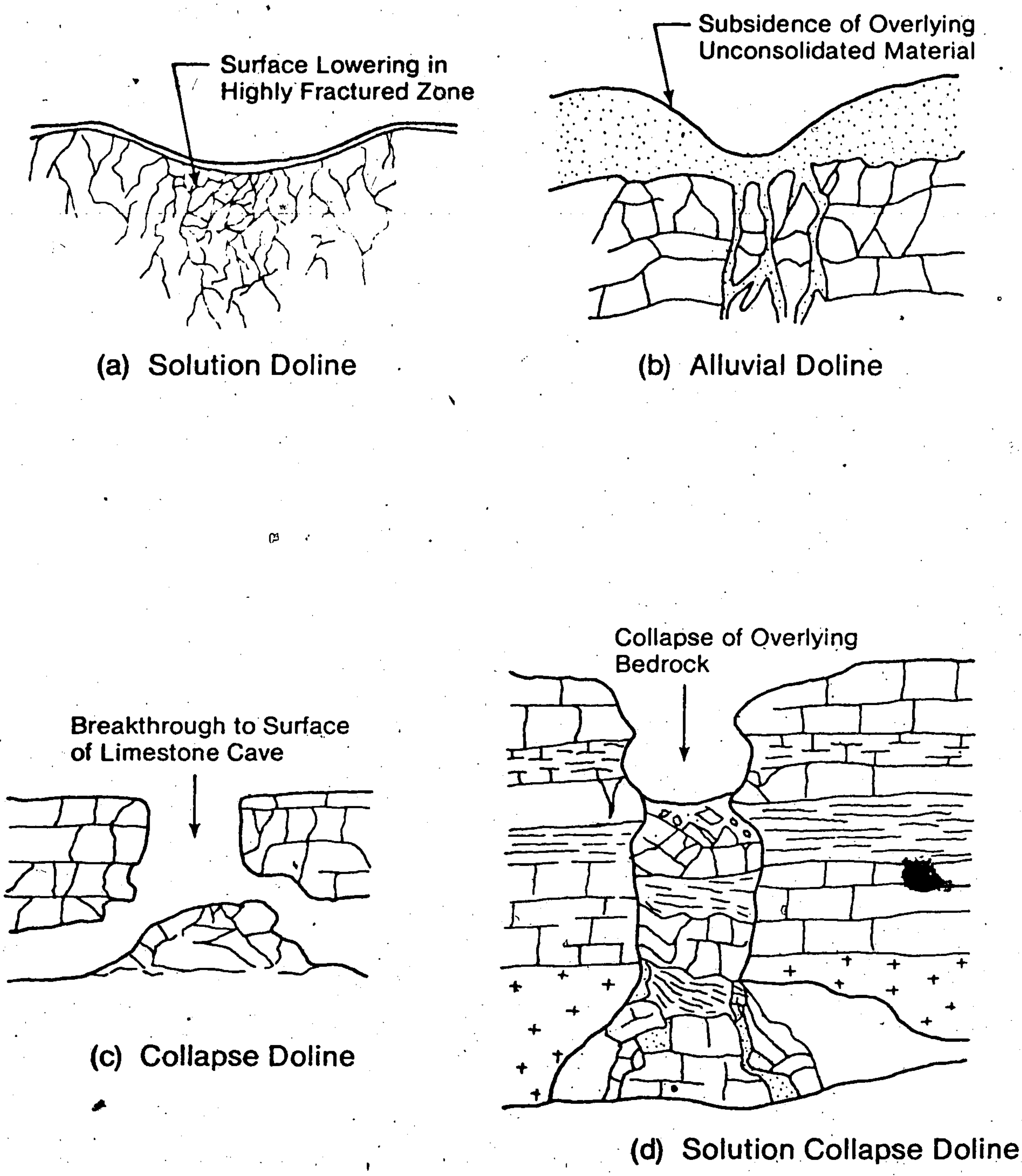


Figure 57. Four Types of Dolines.
(modified from Williams, 1966)

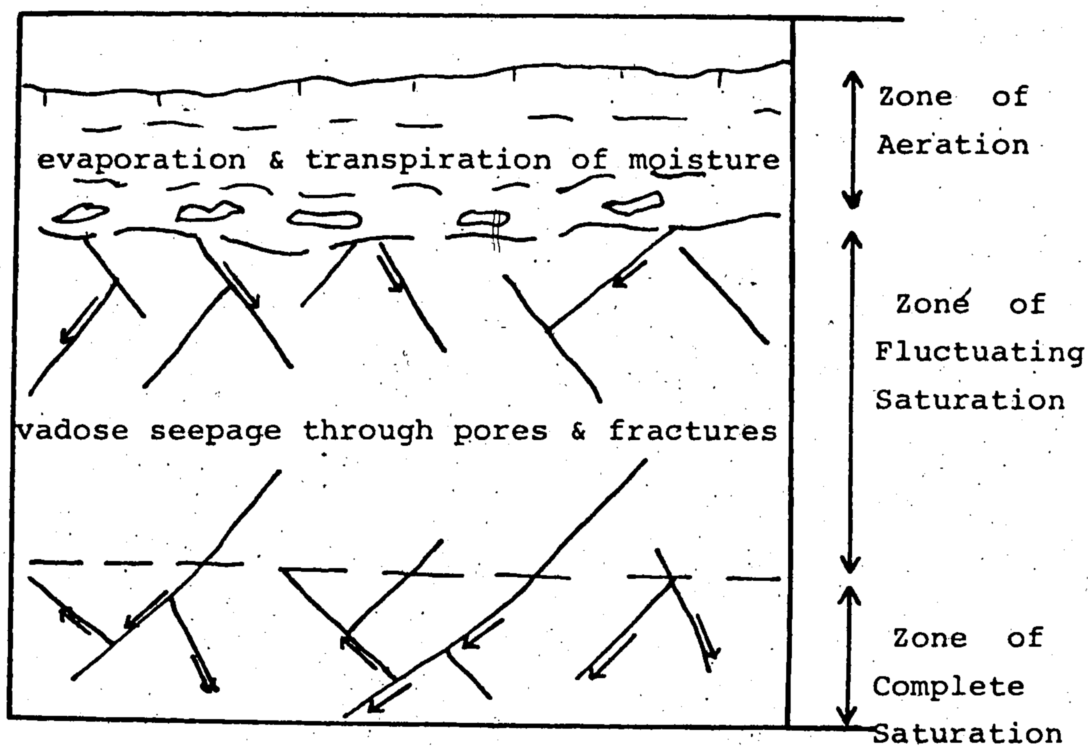


Figure 58. Groundwater Zonation.

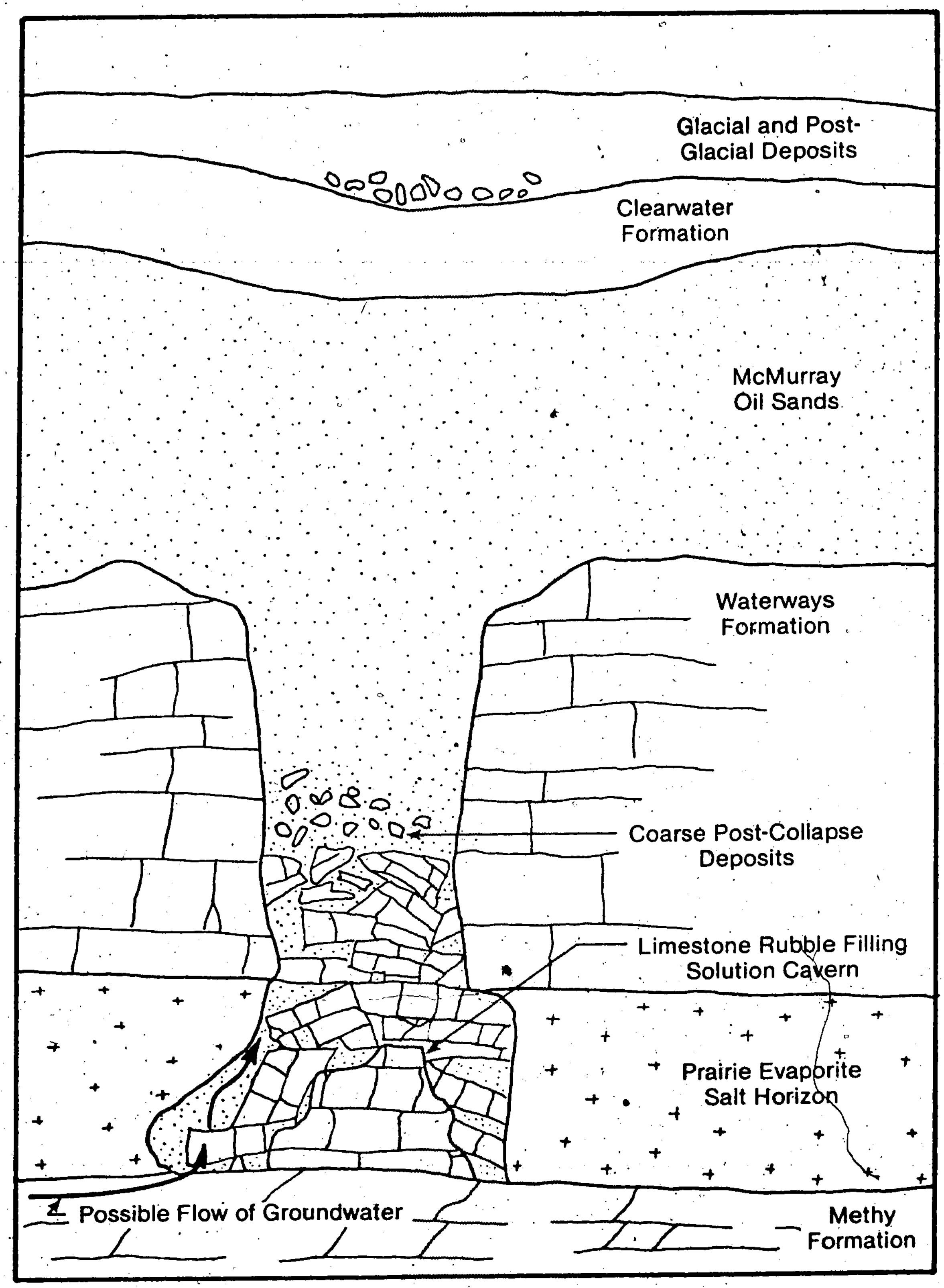


Figure 59. Possible Solution Collapse in the Waterways Formation.

Flow system	System or series	Rock unit (symbol*)		Lithology
Flow system III	Pleistocene and Recent	Glacial drift (Qd)		Glacial till, sand, silt, and gravel
		Erosional unconformity		
	Upper Cretaceous	Smoky Group		Shale
		La Biche Formation		Shale
		Dunvegan Formation		Sandstone
		Shaftesbury Formation (Ksh)		Shale
	Lower Cretaceous	Pelican Formation		Sandstone
		Joli Fou Formation		Shale
		Grand Rapids Formation (Kg)		Lithic sand and sandstone
		Clearwater Formation (Kc)		Shale, siltstone, and glauconitic sandstone
		McMurray Formation (Km)		Quartzose sand impregnated with heavy oil
		Erosional unconformity		
Flow system II	Upper Devonian	Woodbend Group	(Dbl+)	Limestone reef, shale, and shaly limestone
		Beaverhill Lake Formation (Dbl)		Argillaceous limestone, calcareous shale
		Slave Point Formation		Limestone and dolomite
	Middle Devonian	Fort Vermilion Formation	(Dpe+)	Anhydrite and dolomite
		Watt Mountain Formation		Shale and anhydrite
		Muskeg Formation		Anhydrite and dolomite
		Prairie Evaporite Formation		Anhydrite and salt
Flow system I		Methy Formation (Dm)	(Dm+)	Reefal dolomite
		(Keg River-equivalent)		Dolomite, claystone, and evaporites
		McLean River Formation		Claystone and arkosic sandstone
		(Chinchaga-equivalent) (Dmr)		
		La Loche Formation (Dl)		
	Precambrian (Pc)			Metasedimentary rocks and granite

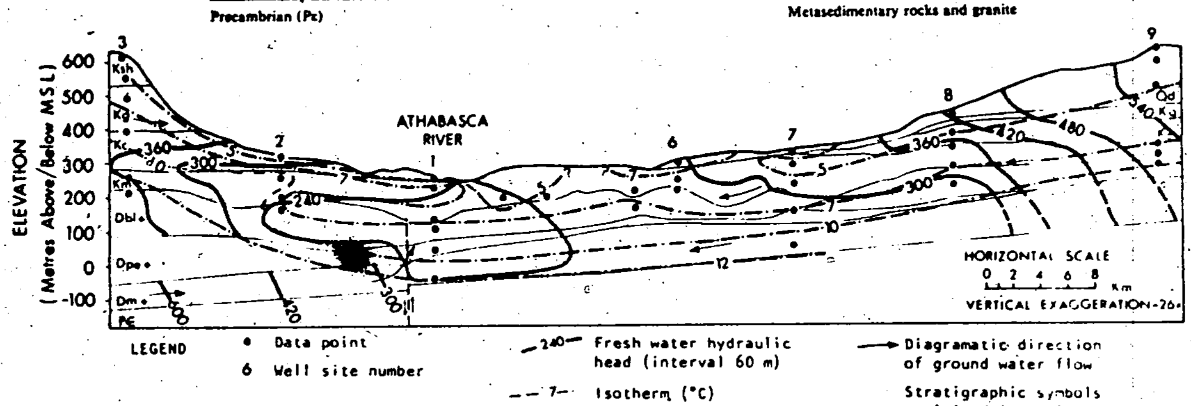
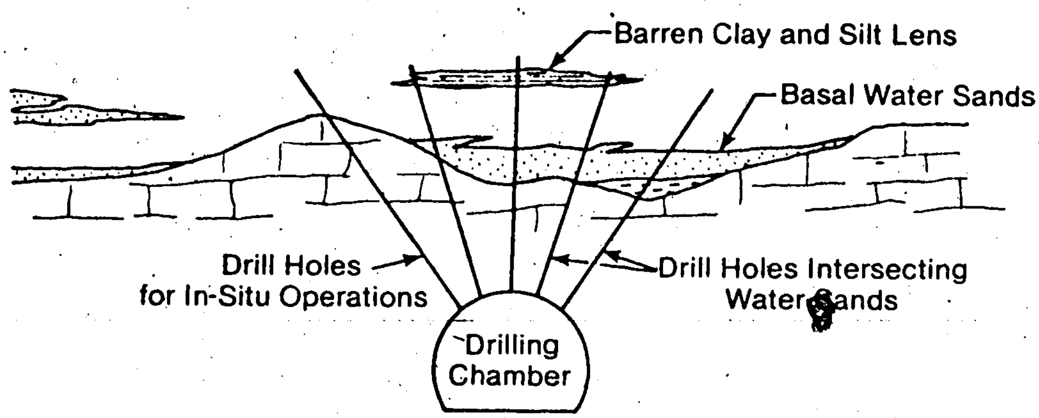
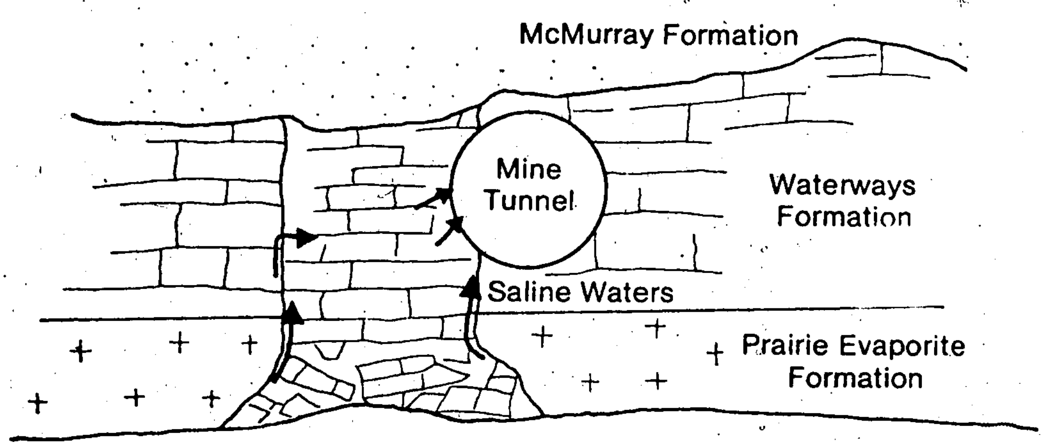


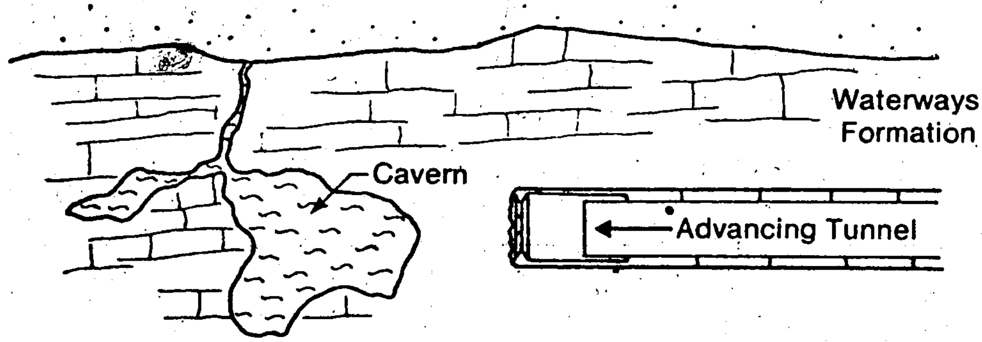
Figure 60. Groundwater Flow Systems and Regional Flow in the Oil Sands Region (from Hackbarth, 1968).



(a) High Pressure Water in Water Sands Near Base of McMurray Formation



(b) Saline Water Entering Mine From Below



(c) Water Filled Caverns Within Waterways Formation

Figure 61. Diagram Illustrating Potential Groundwater Hazards.

ITEM	MASSIVE	#	NODULAR	#	SHALY	#
1 RQD	excellent (90-100%)	95	good (75-90%)	88	good (75-90%)	79
2 Joint Set No.	three sets and random	12	three sets and random	12	three sets and random	12
3 Joint Roughness	discontinuous	4	rough, undulating	3.5	rough, undulating	3.5
4 Joint Alteration	unaltered stain only	1	slightly altered stained	1.5	slightly altered clay coating	2
5 Joint Water	minor inflow	1	minor inflow	1	minor inflow	1
6 Stress Reduction Factor	competent loose joints (clay-free)	3.5	competent loose joints loose rock surrounding	4.5	mild squeezing and swelling weak zones with clay	5.5
TOTAL Q	9.0 - Fair		3.8 - Poor		2.1 - Poor	
Roof Support Pressure	0.28 KPa		0.42 KPa		0.52 KPa	
Wall Pressure	0.18 KPa		0.28 KPa		0.33 KPa	
Support	None if span<6.5m 6.5-14.4m = Bolting@@1-1.5m		None if span<5.9m 5.9-10.9m = Bolting@@1m		None if span<4.5m 4.5-10.4m = Bolting@@1m	

Figure 62. Rock Mechanics Classification of the Waterways Formation - Barton, Lien and Lunde (1974).

ITEM	MASSIVE	#	NODULAR	#	SHALY	#
1. RQD	class 1 very good 90-100%	16	class 2 good 75-90%	14	class 3 fair 50-75%	12
2. WEATHERING	class 1 unweathered	9	class 2 slightly weathered	7	class 3 moderately weathered	5
3. INTACT STRENGTH	class 2 100-200 MPa	5	class 3 50-100 MPa	2	class 5 25 MPa	0
4. JOINT SPACING	class 2-3 0.3-3 m	22	class 2 1-3 m	25	class 3-4 50mm-1m	15
5. JOINT SEPARATION	class 3 ? 0.1-1 mm	4	class 3 ? 0.1-1 mm	4	class 3 ? 0.1-1 mm	4
6. JOINT CONTINUITY	class 1 not continuous	5	class 2 not continuous	5	class 2 discontinuous	5
7. GROUND-WATER	class 3 slight ?	8	class 3 slight ?	8	class 3 slight ?	8
8. JOINT ORIENTATION	class 3 fair ?	10	class 3 fair ?	10	class 3 fair ?	10
TOTAL QUALITY	Class 2 Good rock	79	Class 2 Good rock	75	Class 3 Fair rock	59
Stand-up time	6 months		6 months		1 week	
Active span - Unsupported	4 metres		4 metres		3 metres	
Support Guidelines	Rock bolts, 1.5-2m spacing. Occasional wire mesh in crown. 50mm shotcrete in crown only.				Bolts, 1-1.5m spacing. Mesh plus 30mm shotcrete as needed in crown. 100mm in crown, 50 in walls.	

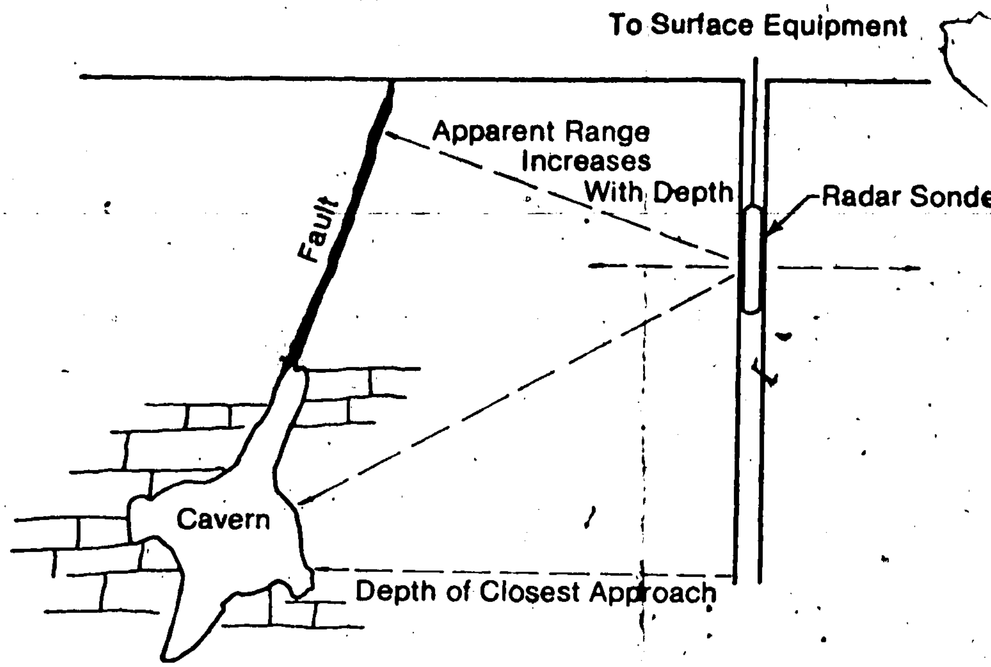
Figure 63. Rock Classification of the Waterways Formation - Method of Bieniawski (1973).

ITEM	MASSIVE	#	#	NODULAR	#	#	SHALY	#	#
1. RQD	Class 1a 91-100%	20	20	Class 1b 76-90%	18	17	Class 2b 56-65%	13	12
2. INTACT STRENGTH	Class 2b 96-110 MPa	7	7	Class 4b 36-50 MPa	3	3	Class 5a-b 5-20 MPa	1	1
3. JOINT SPACING	0.6/0.6/1.0	11	11	0.5/1.0/1.5	15	15	0.1/0.3/1.5	6	6
4. CONDITION OF JOINTS	wavy, striated	29	29	wavy striated surface softer than wall rock	21	19	wavy striated surface softer than wall rock	21	17
5. GROUNDWATER	moist only?	7	7	moist only?	7	7	moist only?	7	7
TOTAL QUALITY	Class 2a Good rock	74	74	Class 2b Good rock	64	61	Class 3b Fair rock	48	43
SUPPORT GUIDE FOR TUNNELS	not required			not required			patterned grouted bolts at 1m spacing		

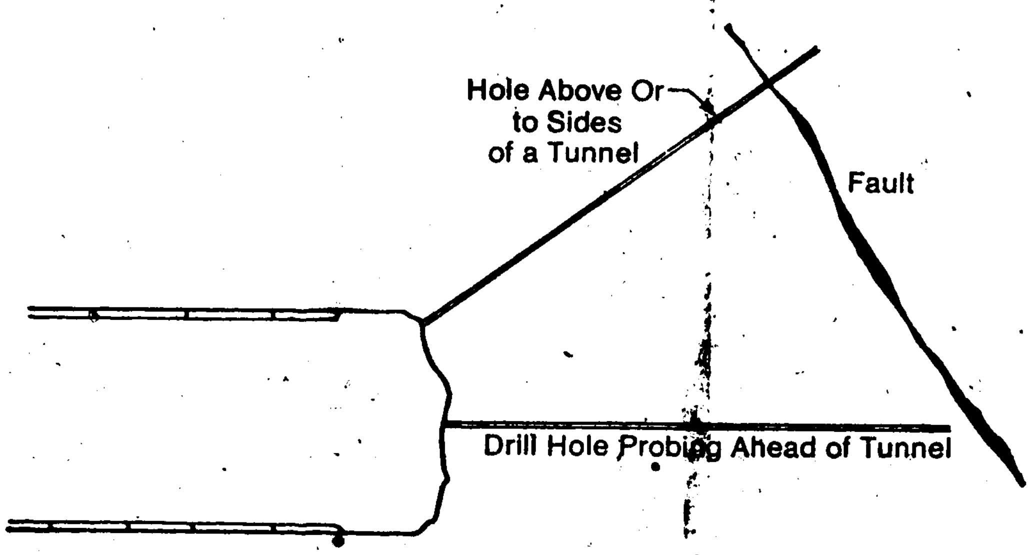
Figure 64. Rock Classification of the Waterways Formation - Method of Laubscher (1975).

ITEM	SYSTEM OF ROCK MECHANICS CLASSIFICATION		
Rock Type	Barton	Bieniawski	Laubscher
1. ROCK QUALITY			
a) Massive	Fair	Good	Good
b) Nodular	Poor	Good	Good
c) Shaly	Poor	Fair	Fair
2. SUPPORT	bolting...	bolting...	
a) Massive	1-1.5m spacing	1.5-2m spacing	not required
b) Nodular	1m spacing	1.5-2m spacing	not required
c) Shaly	1m spacing	1-1.5m spacing mesh&shotcrete as needed	bolting 1m spacing
3. MAXIMUM UNSUPPORTED SPAN			
a) Massive	6.5m	4m	
b) Nodular	5.9m	4m	N/A
c) Shaly	4.5m	3m	
4. STAND-UP TIME			
a) Massive		6 months	
b) Nodular	N/A	6 months	N/A
c) Shaly		1 week	
5. ROOF/WALL SUPPORT PRESSURE			
a) Massive	0.28/0.18 KPA		
b) Nodular	0.42/0.28 KPa	N/A	N/A
c) Shaly	0.52/0.33 KPa		

Figure 65. Table of Comparison of Rock Mechanics Classification of the Waterways Formation.



(a) Radar Exploration From Surface Drill Hole



(b) Exploring Ahead of Tunnel

Figure 66. Ground Exploration Using Drill Holes and Geophysical Methods From Surface or Underground (Modified After Cook, 1974).

Researcher	Unit and Location	CaCO3%	MgCO3%	Clay%	Other%	Lithology
Holter (1963)	middle Moberly at Fort McMurray	86-88	4.3-2.6	-	-	Clayey Lst.
	lower Moberty at 2-6 Km. east of Fort McMurray	87-91	3.2-2.4	-	-	Clayey Lst. Shaly interbeds
	Christina Member at junction of Christina and Clearwater	66	2?	?	15.3% Fe O	Clayey Lst.
	Calumet Member at Clearwater R. 2.5 Km east of Christina junction	79	5.1	?	?	Silty Clayey Lst.
RCA Files	Firebag? Member well 9-1-80-8W4	51	4		SiO =31.5 Al O=7.1 Fe O=2.8	Shale
Carrigy (1959)	Moberly Member at Fort McMurray	95.18	1.11	-	SiO =1.66 Al O=1.20 Fe O =0.21	Limestone
This Study (1978-1979)	All from Moberly Member	97.7	(v low)	2.3		Biolithic Lst. sparry
		95.9	(v low)	4.1		Aphanitic Lst very sparry
		75	(low)	26	Variably low pyrite (0-2%)	Disseminated Argillaceous Micrite
		81.7	(v low)	18.3	variable (1.3%)	Nodular Lst. low-clay
		62	(v low)	38	variable pyrite	Nodular Lst. high clay
		39.3	(v low)	60.7	-	Calcareous shale

Figure 67. Table of Carbonate Analysis of the Waterways Formation.

Class	Minimum specific gravity	Maximum deleterious materials (pct)	Maximum abrasion loss (pct)	Maximum soundness loss (pct)	Maximum absorption (pct)
A	2.45	5	40.0	12	3
B	2.45	6	45.0	16	
C	2.45	10	50.0	20	

Figure 68. Table of Limestone Classification for Use as Aggregate (From Indiana State Highway Commission, 1969).

Physical Test	ASTM No	AASHO No
Aggregate:		
Abrasion:		
Deval machine	D289-63	T 3-35**
Los Angeles machine	C131-66	T 96-65
Amount of Material finer than no. 200 sieve in aggregate		T 11-60
Determination of clay lumps in natural aggregates	C142-64	T112-64
Scratch hardness of coarse aggregate particles	C235-62	T189-63
Sieve analysis of fine and coarse aggregate	C136-67	T 27-60
Soundness:		
Sodium sulfate	C 88-63	T104-65
Freeze and thaw		T103-62
Specific gravity and absorption of coarse aggregate	C127-68	T 85-60
Specific gravity and absorption of fine aggregate	C128-68	T 84-60
Dimension Stone:		
Abrasion resistance of stone subjected to foot traffic	C241-51	
Compressive strength of natural building stone	C170-50	
Modulus of rupture	C 99-52	

Figure 69. Table of Physical Tests of Carbonates to Determine Suitability for Use as Aggregate or Dimension Stone (ASTM and AASHO).

Plate 1. Gentle Domal Folds in the Waterways Formation (Mackay River Outcrop).

Plate 2. Core Hole WW1. Long Pieces of Aphanitic Lst; also Banded and Nodular Lst (bottom).

Plate 3. Lithology Types from Core Hole WW1. Massive, Aphanitic, Nodular, Disseminated and Banded Shaly Limestone.

Plate 4. Bedding in the Moberly Member, Mountain Rapids Outcrop.

Plate 5. Irregularly Spaced Jointing with Fractures, Mountain Rapids Outcrop.

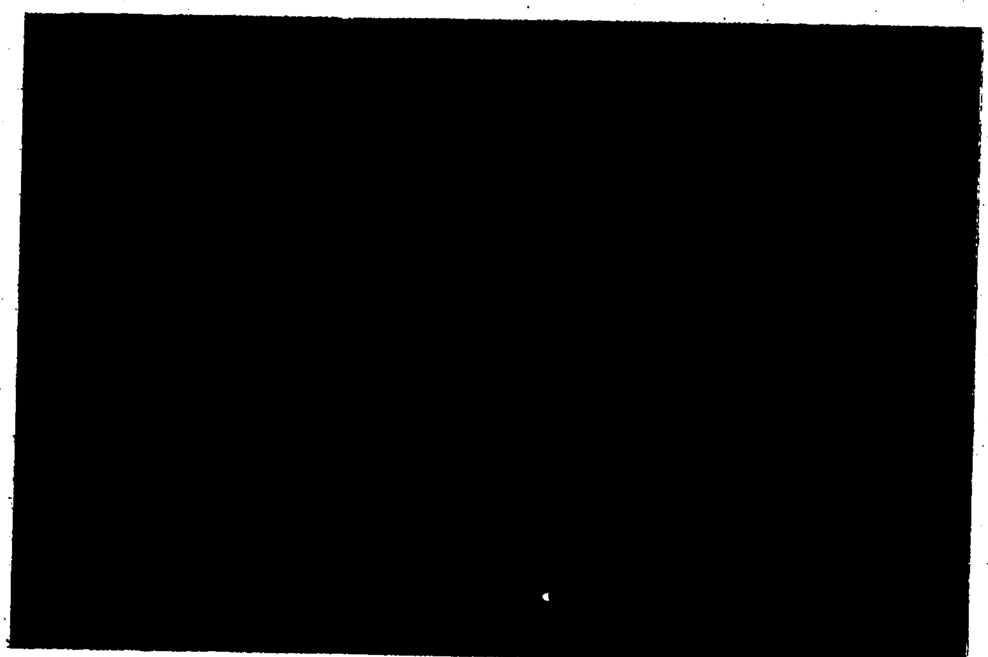


Plate 6. Discontinuous and Non-Planar Joints in the Moberly Member, Mountain Rapids Outcrop.

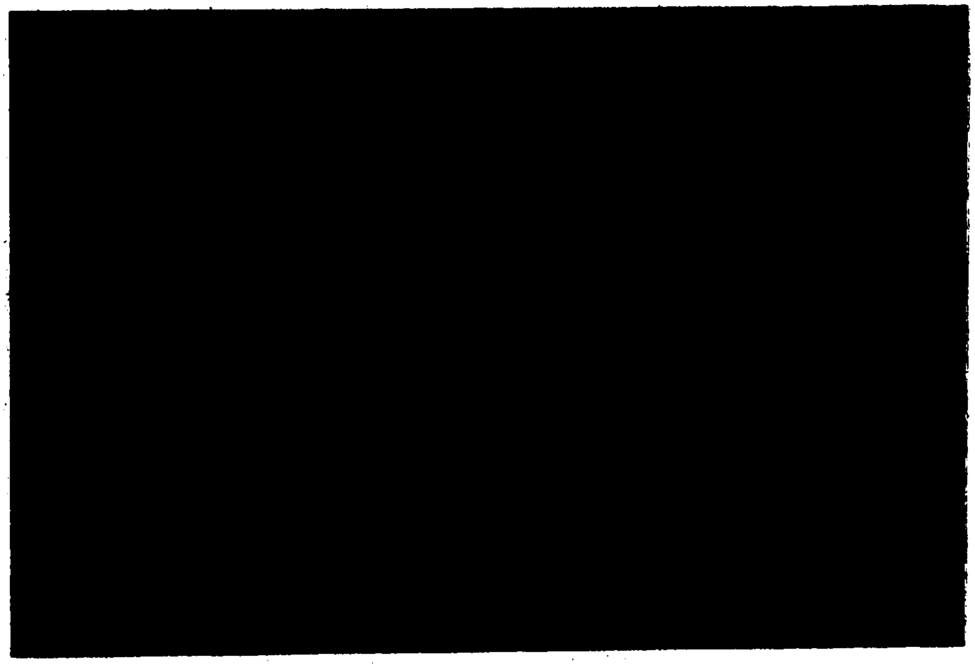


Plate 7. The Direct Shear Testing Equipment.

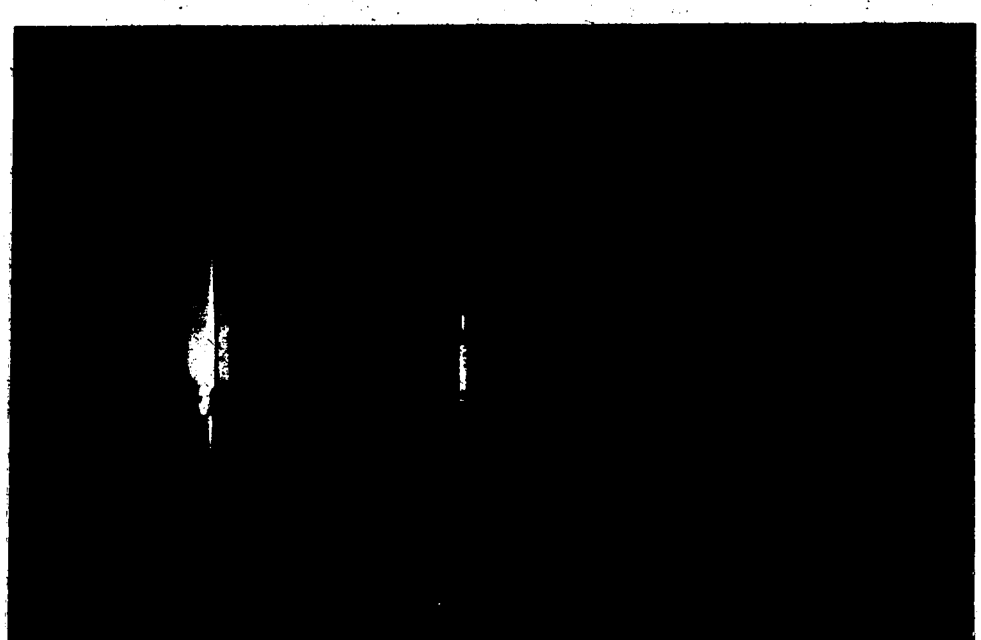
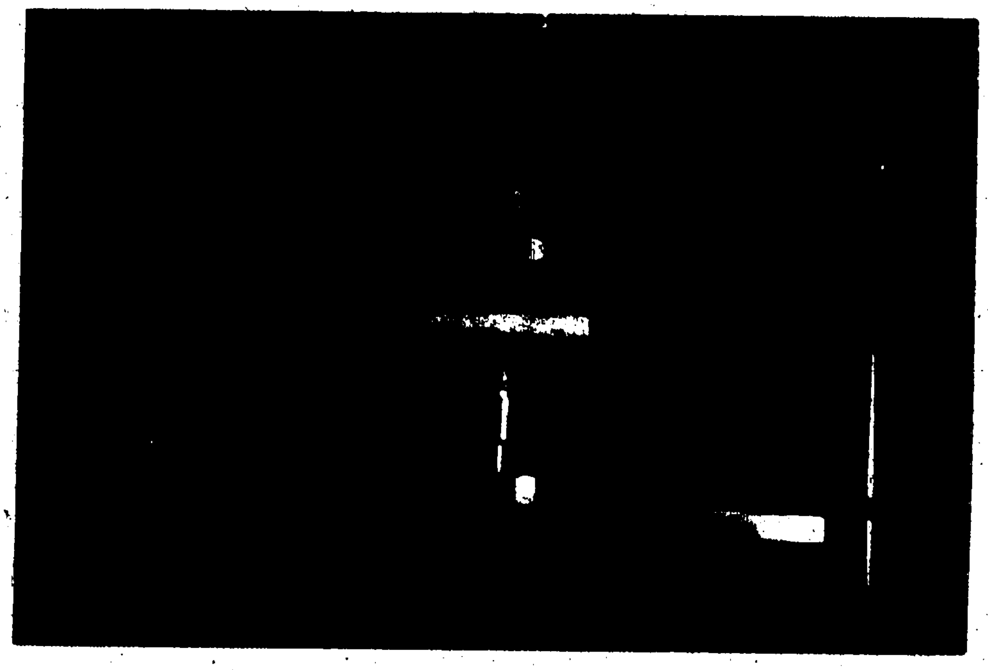


Plate 8. The Direct-Pull Tensile Test.



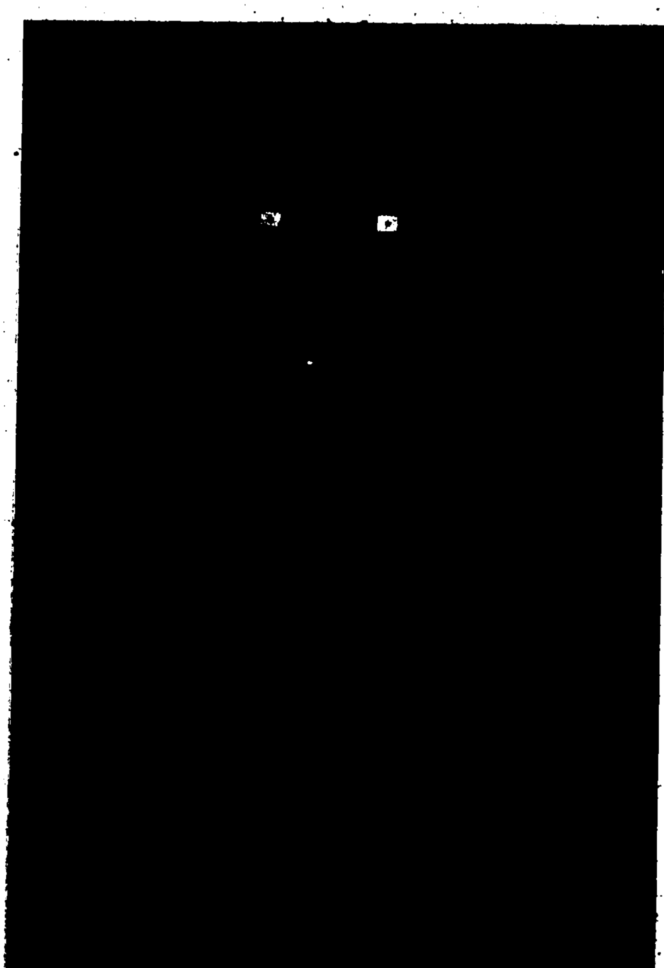


Plate 9. The Four-Point Bending Test.

Plate 10. The Brazilian Test.

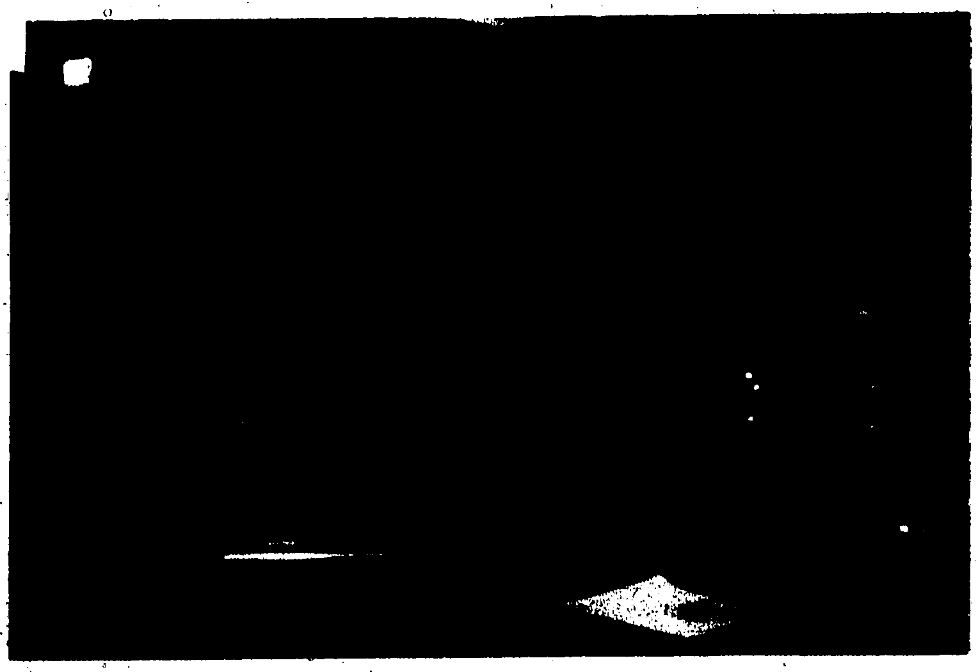


Plate 11. The MTS Compression Frame with Triaxial Cell and Control Panel.

Plate 12. Point Load Testing of Field Samples.

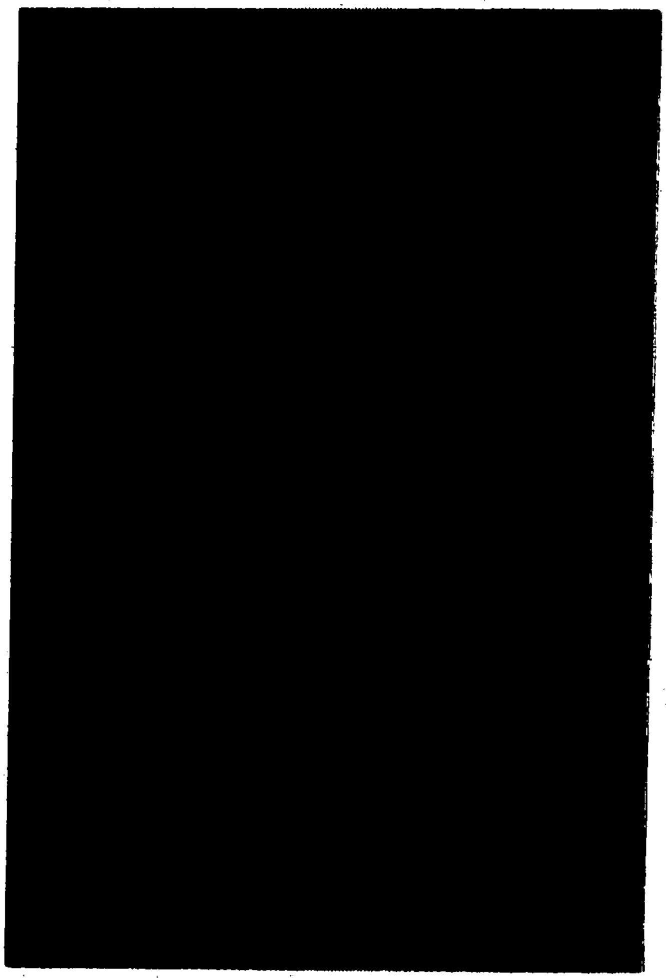
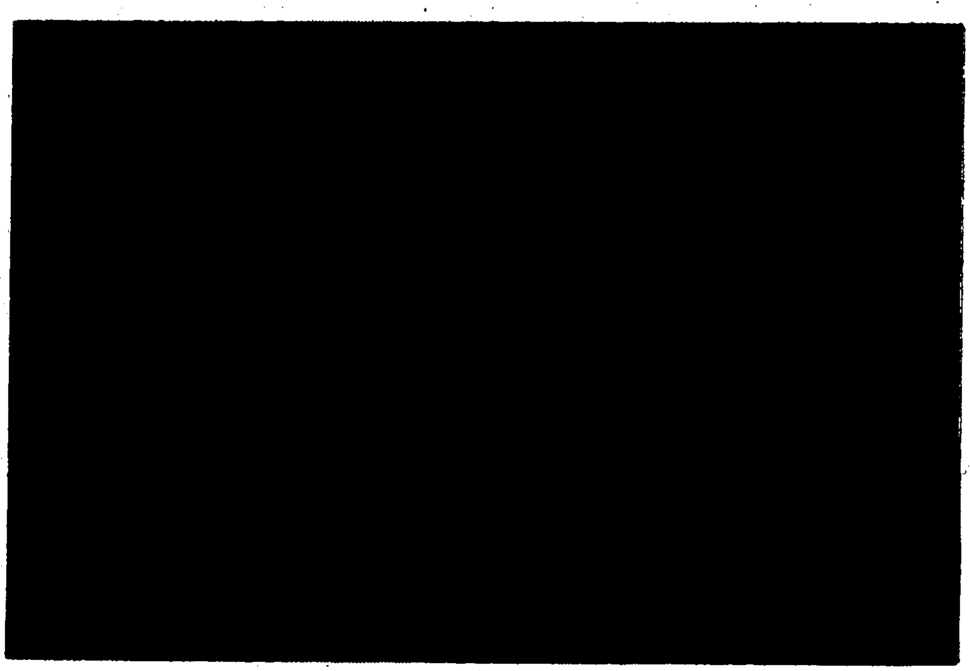


Plate 13. Bitumen Impregnation in Waterways Formation Limestone (photo by EBA Engineering).

Plate 14. The Oil Sand /Limestone Contact, with Weathered Lst below.



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APPENDIX A

List of Wells Penetrating The Waterways Formation

(Numbers correspond to well numbers on map, figure 6)

	Well Name	Location	Waterways Formation Intersection
1.	Shell Eatha EV	12-6-99-8W4	cored 3[illegible]-440′
2.	Shell Eatha EV	13-31-96-6	[illegible]10-498′ cored 355-366′ and [illegible]77-498′
3.	Texex Steepbank3	15-32-94-7W4	cored 743-754′
4.	Texex Steepbank1	10-24-93-7W4	cored 844-862′
5.	Texex Steepbank2	4-14-93-7W4	cored 739-746′
6.	EBA CE0003 #1	Shell Lease c13	cored 3-48′
7.	#2	"	cored 3-48′
8.	#3	"	cored 8-48′
9	#5	"	cored 3-43′
10.	#6	"	cored 3-43′
11.	#7	"	cored 7-43′
12.	#9	"	cored 13-48′
13.	#10	"	cored 3-48′
14.	#11	"	cored 3-47′
15.	#12	"	cored 7-41′
16.	Thurber 78-1 to 5	Bridge Site 1	Electrologs Only
17.	78-6	Bridge Site 1	cored 34-68′
18.	79-1	Site 1	cored 12-40′
19.	79-2	Site 1	cored 11-38′
20.	79-3	Site 1	cored 36-64′
21.	79-4	Site 1	cored 37-64′
22.	79-6	Site 1	cored 33-66′
23.	79-7	Site 1	cored 34-62′
24.	79-8	Site 1	cored 36-52′

25.		79-9	Site 1	cored 35-54′
26.		79-10	Site 1	cored 40-67′
27.		79-11	Site 1	cored 39-65′
28.		74-1	Bridge Site 3	cored 40-54′
29.		74-2	Site 3	cored 18-32′
30.		74-6	Site 3	cored 58-73′
31.		74-8	Bridge Site 2	cored 96-98.5′
32.	Hardy	TH-1	PetroCanada MAISP	cored 5.4-17.6m
33.		TH-2	MAISP	cored 7.3-11.1m
34.		TH-3	MAISP	cored 5.9-17.1m
35.		TH-4	MAISP	cored 63.4-72.5m
36.	Syncrude 1		6-30-92-10W4	cored 224-248′
37.	Syncrude 2		15-19-92-10W4	cored 231-[illegible]
38.	AOSTRA/U of A WW1		GCOS Mine	cored 0-102′
39.	Baysel Birch Hills		9-34-94-14W4	cored 598-609′
40.	Athabasca Oils No 1		8-2-96-11W4	155′-590′
41.	Bear Vampire No 2		4-32-93-10W4	11′-429′
42.	Bear Rodeo No 2		5-17-91-9W4	10′-458′
43.	Bear Rodeo No 1		8-20-89-9W4	33′-476.5′
44.	Alta & Great Western		SE10-89-9W4	151′-643′
45.	Industrial Min Salt #1		SE10-89-9W4	100′-478′
46.	" Salt #2		SE10-89-9W4	151′-513′
47.	" Salt #3		SE10-89-9W4	
48.	Alta Government Salt No 1		Lot 8 89-9W4	95′-497′
49.	" Salt No 2		32-88-8W4	40′-415′
50.	Bear Westmount No 2		8-36-88-8W4	5′-399′
51.	Bear Westmount No 1		14-9-86-7W4	865′-1264′
52.	Bear Vampire No 1		7-28-87-12W4	cored 642-918′
53.	Bear Biltmore No 1		7-11-87-17W4	981′-1682.5′

54.	RO Corp Divide		6-36-82-12W4	cored 1680-1693′
55.	HB Thornbury EV		5-19-78-12W4	cored 1490-1530′
56.	Gulf Pony 1		6-8-81-9W4	cored 1574-1590′
57.	Gulf Pony 2		6-25-81-9W4	cored 1464-1567′
58.	Numac Surmont	E1	8-25-85-7W4	cored 1152-1159′
59.	"	E2	7-29-83-7W4	cored 1510-1522′
60.	"	E3	8-25-83-7W4	cored 1148-1158′
61.	"	E4	8-25-83-7W4	cored 1142-1150.5′
62.	"	E5	7-8-83-7W4	cored 1602-1612′
63.	"	E6	7-29-83-7W4	cored 1505-1522′
64.	Richfield Bohn Lake #1		15-29-79-5W4	cored 1046-1086′
65.	Merrill-Arab. Chard		5-34-78-6W4	cored 1193-1216′
66.	Home Christina Lake		3-3-78-6W4	cored 1372-1387′

Overburden.

UNIT 8. Massive (30 cm). Inaccessible. Hard and resistant; well jointed.

UNIT 7. Platy micritic limestone. 90 cm. Inaccessible. Platy weathering; weak joints in a few places only.

UNIT 6. Nodular. Inaccessible. 30 cm. Rusty stained. Strong and resistant; broken by several planar joints.

UNIT 5. Nodular (about 60 cm). Inaccessible. Nodular weathering. No joints visible.

UNIT 4. Massive (2.3 m). Very well jointed.

Weathers to brittle shards in some places but generally seems to break well with no shaly partings. Bed thickness varies from 15 - 60 cm, but can be more thinly parted and fractured. Forms blocks of 30x60x60 cm down to blocks 20x20x2 cm. Uniformly light buff grey, finely and densely cryst with low porosity. Hard=1, very calcareous. Moderately fossiliferous.

UNIT 3. (60 cm). Shaly Micritic Limestone. Weathers platy to nodular. Forms lenses of three types:
a) dense dark grey, finely cryst lime mud 5 cm thick
b) recryst fossils, hard and brittle, 5 cm.
c) soft shaly material 1 cm thick. Dense muddy lenses are dark and cryst; shaly lenses are lt grey silty appearing. Both v calcareous.

UNIT 2. Massive (60 cm). The entire unit is very well jointed, has scattered marcasite is hard, massive and has blocky weathering.

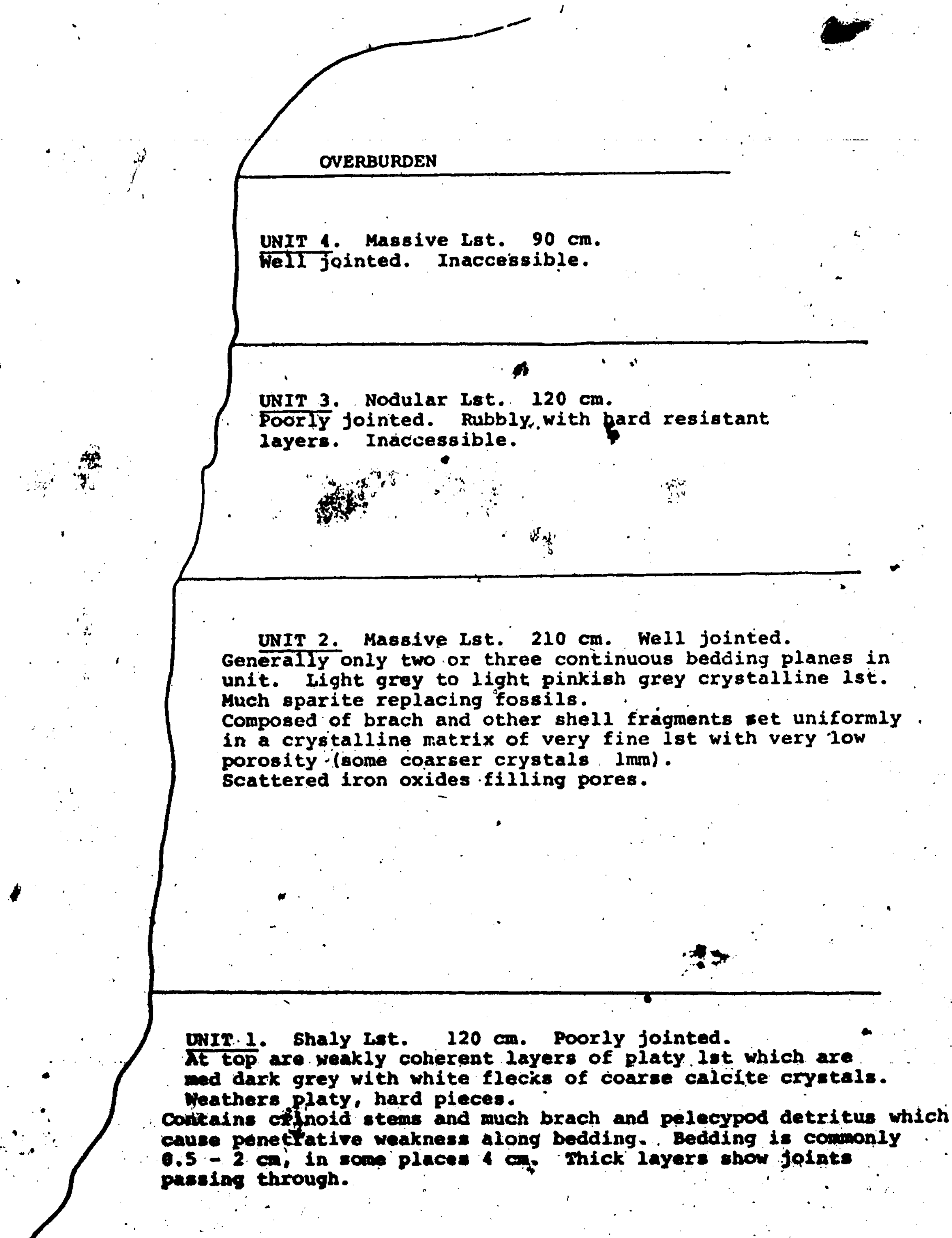
Upper part (15 cm) - fossil bed with brachs, crinoids, etc. Fair porosity, hard=2, v calcareous. Much sparite recryst of fossils. Lenses of dark grey finely cryst lst, 2-3 cm thick forms 20% of layer. Rsty pores, limonitic. Breaks well along bedding.

Mid part (30-40 cm) - light pinkish brown, fine-v fine cryst lst. Breaks conchoidally - very brittle, hard=1, very calcareous. Matrix of fine-micro ryst material around fossils.

Basal 5cm - very fossilif. Med grey, less brittle; breaks in rounded lumps.

UNIT 1. Nodular Lst (max 120 cm). Unit weathers into nodules with platy layers at base and middle.
Nodules are light grey, densely and uniformly cryst lst with clay film which weathers easily. Nodules are 2-5 cm.
Platy layers are speckled med-dark grey, med cryst lst, formed of coarse calcite crystals 2 mm. Some layers of recryst crinoids and brachs with layers of very uniform and dense light grey lst. Some areas appear pseudo-brecciated with fossils.

MOUNTAIN OUTCROP. Outcrop of Waterways Formation, Moberly Member at Mountain Rapids, upper Athabasca River.



MOBERLY OUTCROP. Outcrop of Waterways Formation, Moberly Member at Moberly Rapids, Athabasca River.

UNIT 5. Shaly Lst. (90 cm). Some jointing.
Upper 60 cm is med greyish brown, dense and finely crystalline with moderate fossil content. Towards top becomes microcrystalline, aphanitic, with conchoidal fracturing. Weathers partly nocular, partly platy.
Basal 30 cm is shaly weak and rusty lst. Part is good fissile shale weathered to clay.

UNIT 4. Massive Stromatoporoid Lst. Well jointed. 180 cm.
Light pinkish grey, even textured, medium to coarsely crystalline at base becoming fine to medium at top.
Much recrystallization of fossils, with some being entirely replaced with sparite. Well cemented and glassy.
Rich in brachiopods and in stromatoporoids up to 40 cm.

UNIT 3. Argillaceous Lst. 60 cm. Very poorly jointed.
Med grey finely crystalline, moderately argillaceous.
Weathers into nodular shards forming loose rock.
Weak and recessive.
At base is 20 cm layer of shells which are recrystalized and platy.

UNIT 2. Fossiliferous Lst. 60 cm. Well jointed.
Hard and massive and very fossiliferous.
Med grey, finely crystallized and dense and well indurated.
Weathers to small blocky to angular, platy blocks.
Grades upwards into the argillaceous unit 3.

UNIT 1. Shaly Lst. 120 cm. No regular jointing.
Recessive, weathers into small platy slabs of finely crystalline, light greenish grey nodules of lst set into brownish clay. Very weathered into broken rubble.
No jointing is visible in the very rubbly weathered places.
No fossils were found.

STONY OUTCROP. Outcrop of Waterways Formation, Moberly Member at Stony Island Outcrop, Athabasca River.

OVERBURDEN

UNIT 6. Shaly Lst. 120 cm. Inaccessible.
Rubbly weathering into 10 cm blocks.
No planar jointing visible.

UNIT 5. Massive Lst. 240 cm.
Contains large planar joints.
Light grey, finely crystalline, with lenses of fossiliferous lst (corals and stroms) - lenses are 2 x 15 cm to 2 x 30cm.
A resistant, cliff-forming unit.

UNIT 4. Nodular Lst. 160 cm. Well jointed near base.
Light tan colored, microcrystalline with sparite recrystallization or coating on brachs.
Weathers into 4 cm chunks - rubbly.
Base is light tan with many fossils. Very highly recrystallized. Good joints faces near base.

UNIT 3. Argillaceous Lst. Platy to Nodular. 160 cm.
Weathers into small (2x4x4 cm) hard chips; recessive.
Light tan colored, microcrystalline; much sparite recrystallization destroys previous texture of ?fossils.

UNIT 2. Nodular Lst. 150 cm. Poorly jointed.
A weak and rubbly unit; surface weathering into nodules prevents exposure of fresh outcrop.
Med tan-brown, microcrystalline with conchoidal fracture.
No fossils recognizable - much sparite recrystallization.

UNIT 1. Shaly Lst. 90 cm. Poorly jointed.
Platy and fairly resistant.
Varies from microcrystalline to finely crystalline lst.
The microcrystaline is light tan, very dense and calcareous, with low porosity. The finely crystalline is light grey with many coarse calcite crystals and fair porosity; very calcareous.
All of unit is fossiliferous - many brachs which are generally recrystallized or coated with sparry calcite.

MACKAY OUTCROP. Outcrop of Waterways Formation, Moberly Member Near Lookout Point, Mackay River.

APPENDIX B

ROCK TYPE and NUMBER OF TESTS

Test	Biolithic	Aphanitic	Nodular	Diss Arg.	Shaly	Other
Uniaxial	20	22	10	8	-	3
Direct-Pull	7	9	-	-	-	-
Brazilian	16	2	27	27	-	9
Four-Point Bending	-	4	-	-	-	-
Triaxial	7	8	8	8	-	-
Double Shear	0	8	8	-	-	-
Point Load	8	2	1	-	5	(2cores)
Impact Toughness	-	2	3	1	-	-
Slake Durab.	2	-	10	2	5	-
Swelling	-	-	-	-	3	-
Direct Shear	1(j)	1(j)	5j+2b	-	1(b)	-

TABLE OF TEST DATA FOR THE FIVE MAJOR LITHOLOGIES OF THE WATERWAYS FORMATION

TEST RESULTS - BIOLITHIC LIMESTONE

Sample No	Strength (MPa)	Diam (mm)	L/D	Velocity (m/secx10)	Density (g/cc)	Moisture (%) (Iv/totIv)	Ox	Strain (%)	Time Submerged (days)	Orient to Bed	Fail Angle (°)	Load Rate (mm/min)
20 Uniaxial Compression Tests:												
Bayb1	100.1	32.64	1.94		2.63		1		8	perpendic		0.203
Bayb2	116.7	32.60	1.99		2.63		1		0	"		0.203
Bayb3	120.8	32.59	2.02		2.63		1		0	"		0.203
45.b	73.8	54.05	1.91		2.53	/2.3%			0	"		0.203
49.a	43.4	75.40	2.09		2.59				0	"		0.203
51e1		30.04	1.74	3920	2.53	1.4/	4		0	parallel		0.203
80b	75.6	75.35	1.94	4230	2.76		3		0	"	60	0.203
106h	120.0	40.89	2.02		2.61		2	0.44	0	"		0.102
107b	73.7	41.17	1.85	5300	2.60	0.6/	2	0.48	52	"		0.203
107c	63.1	41.19	1.86	5270	2.61	0.4/0.61	2	0.44	52	"		0.203
107f	140.6	41.20	2.02	5590	2.63	0.3/	2	0.60	52	"		0.203
108a	81.1	41.25	2.00	5470	2.49	0.3/	1	0.52	52	"		0.203
109a	112.3	54.16	2.23	5360	2.63	0.3/	1	0.48	52	"		0.203
111b	132.7	54.14	2.06	5400	2.47	0.4/	2	0.44	52	"		0.203
112a	87.4	54.06	2.10	5330	2.60	0.3/	1	0.49	0	"		0.203
113a	139.8	54.10	1.90	5620	2.62	0.3/	1	0.57	0	"		0.203
Mtn1D1	143.4	54.00	2.07		2.72		1	0.57	5	"	65	0.102
Mtn1D2	154.9	54.00	2.08		2.72		1	0.55	5	"	90	0.203
Mtn1D3	151.5	54.03	1.88		2.70		1	0.58	5	"	75	0.203
Mtn1D4	140.9	54.00	2.04		2.70		1	0.54	5	"	90	0.203
Mtn2D1	102.8	53.97	1.98		2.71	/0.25	1	0.48	5	"	60-90	0.203
Mtn2D2	130.6	54.00	1.92		2.70	/0.31	1	0.55	5	"	90	0.203
Mtn2D3	147.7	53.97	2.03		2.72		1	0.54	5	"	90	0.203
7 Triaxial Compression Tests:												
106a	6.9/114.1	41.15	2.04		2.55		2	0.36	0	perpendic	62	0.102
106b	13.8/169.1	41.20	2.01		2.56		1	0.43	0	"	65	0.102
106c	20.7/189.8	41.17	1.99		2.57		1	0.56	0	"	62	0.102
106d	24.1/252.4	41.20	1.94		2.59		1	0.56	0	"	68	0.102
106e	9.7/246.8	41.17	2.01		2.59		2	0.61	0	"	62	0.102
106f	41.4/251.0	41.15	1.95		2.56		2	0.75	0	"	90	0.102
106g	6.9/123.4	41.20	1.99		2.54		1	0.38	0	"	62	0.102
8 Point Load Tests:												
M1	4.3									perpendicular		
M2	4.4									"		
M2	2.1									"		
M2	2.5									"		
May5	3.0									"		
Stony2	3.1									"		
Ston3foss	2.7									"		
Stony4	2.1									"		

BIOLITHIC LIMESTONE ... continued

Sample No	Strength (MPa)	Diam (mm)	L/D	Velocity (m/secx10)	Density (g/cc)	Moisture (%) (Iv/totIv)	Ox	Strain (%)	Time Submerged (days)	Orient. to Bed	Fail Angle (°)	Load Rate (mm/min)
21 Brazilian Tests:												
51C1a	4.84	41.28	0.58		2.87				28	parallel		
51C1b	5.09	41.20	0.66		2.57				28	↓		
51C2a		41.20	0.74	4780	2.51	1.8/	2		28	↓		
51C2b	7.52	41.20	0.65	4930	2.55	1.2/	2		0	↓		
51C3a	4.66	41.20	0.64		2.51				28	↓		
51C3b	5.66	41.20	0.60		2.51				28	↓		
51D2a	1.90	41.06	0.59	3470	2.51	1.4/	4		28	↓		
51D2b	2.46	41.11	0.56	3690	2.51	1.4/	4		28	perpendic ↓		
51D3	5.59	41.16	0.66	4610	2.51	1.4/	3		28	parallel		
Birch603*1	3.57	32.51	0.52		2.64	/1.63				↓		
Birch603*2	7.31	32.60	0.99		2.69	/1.02			28	↓		
Birch605*1	7.45	32.51	0.63		2.61					↓		
Birch605*2	7.35	32.51	0.48		2.61				28	↓		
Birch605*3	9.45	32.59	0.90		2.70				28	↓		
106h	4.07	74.50	0.41	3500	2.53	0.8/	2		0	↓		
107E1	6.87	41.22	0.51		2.64				28	↓		
107E2	7.63	41.22	0.45		2.67				28	↓		
108B1	8.37	41.24	0.61	4670	2.62	0.4/	2		0	↓		
108B4	7.38	41.20	0.59	5060	2.62	0.4/	1		28	↓		
112bas	6.59	54.00	0.33	5625	2.60		1		0	↓		
SA9		20.99	0.59		2.64		1		28	↓		
1 Direct Shear Test:												
4						4%(sat)	5		1			
7 Direct Tension												
51E2	5.9	24.38	2.75	4290	2.55	1.3/	3		0	perpendic		
51E3	3.96	24.41	2.02	3940	2.53	1.4/	4		0	↓		
51E4	5.1	24.41	2.76	4300	2.56	1.2/	3		0	↓		
51E5	4.67	[illegible]	[illegible]	4250	2.53	1.2/	2		0	↓		
80A1	5.6	25.05	[illegible]	4940	2.61	0.6/	2		0	parallel		
80A2	7.4	24.94	2.31	4560	2.61	0.8/	3		0	↓		
80A3	7.6	25.13	2.49	4800	2.59	0.9/	3		0	↓		
2 Slake Durability:												
NumS1154	Is = 26.8%						4					
NumS1155	Is = 5.7%						5					

TEST RESULTS - APHANITIC LIMESTONE

Sample No	Strength (MPa)	Diam (mm)	L/D	Velocity (m/secx10)	Density (g/cc)	Moisture (%) *(Iv/totIv)	Qx	Strain (%)	Time Submerged (days)	Orient to Bed	Fail Angle (°)	Load Rate (mm/min)
22 Uniaxial Compression Tests:												
41E	86.6	54.00	2.07		2.48			0.40	0	perpendic		0.102
GCOS1a1	95.8	41.12	2.0			/1.52	1	0.12	0	↓		0.102
GCOS1a2	40.6	41.29	2			/1.44	1	0.26	0	↓		0.102
GCOS1a3	50.1	41.13	2				1	0.28	0	↓		0.102
GCOS1a4	47.0	41.15	2				1	0.28	0	↓		0.102
GCOS1a5	57.0	41.15	2				1	0.34	0	↓		0.102
GCOS1a6	50.0	41.02	2				1	0.32	0	↓		0.102
GCOSac1	36.4	32.39	1.97		2.62		1	0.33	0	↓	85	0.102
GCOS1c2	62.4	32.32	2.02		2.66		1	0.33	0	↓	75	0.203
GCOS1c3	23.3	32.64	1.94		2.61		1	>0.42	0	↓	(fragments-creep test)	
GCOS1c4	[illegible]3	32.44	1.89		2.60		1	>0.28	0	↓	(fragments-creep test)	
GCOS1c5	[illegible].9	32.54	2.00		2.62		1	>0.50	0	↓	90	(creep)
GCOS1c6	67.6	32.51	1.97	5340	2.63	05/(0.07=test)	1	0.71	0	↓	70	0.203
GCOS1d1	08.6	54.03	2.08		2.66		1	0.52	5	↓	80	
GCOS1d2	05.6	54.03	2.06		2.66		1	0.48	5	↓	90	0.203
GCOS1d3	15.8	54.03	2.07		2.66		1	0.54	5	↓	80	0.203
GCOS1d4	16.3	54.01	2.08		2.67		1	0.53	5	↓	75	0.203
GCOS1d5	87.0	54.01	2.08		2.66		1	0.47	5	↓	85	0.203
GCOS1d6	09.1	54.03	2.06		2.66	0.99/	1	0.51	5	↓	70	0.203
GCOS1d7	78.7	54.01	2.01		2.66		1	0.44	5	↓	90	0.203
GCOS1d8	18.3	54.00	2.05		2.67		1	0.54	5	↓	75	0.203
GCOS1d9	15.9	54.03	2.06		2.67		1	0.50	5	↓	90	0.203
8 Triaxial (saturated)												
41b	14.8/148.6	54.06	2.13		2.50	2.8 at test		0.35	52	perpendic	85-90	0.102
41c	17.4/155.5	54.13	2.16		2.48	2.9 "		0.44	52	↓	75	0.102
41d	20.7/172.9	54.03	2.07		2.49	2.9 "		0.46	52	↓	62	0.102
41f	7.7/102.2	54.10	2.12		2.49	2.9 "		0.30	52	↓	irreg	0.102
31g	10.5/125.5	54.00	2.03		2.52	2.6 "		0.28	52	↓	85	0.102
41h	27.6/171.1	54.11	2.12		2.51	2.9 "		0.46	52	↓	68	0.102
44b	3.5/ 98.2	53.98	2.10		2.53	2.3 "		0.26	52	↓	90	0.406
45a	8.8/115.7	54.00	1.94		2.53	2.4 "		0.32	52	↓	62	0.102
8 Double Shear Tests:												
42*1	11.9	37.3	>1.5			air dry			0	parallel		
42*2	9.3	"	"			"			0	"		
43a1	14.0	"	"			"			0	perpendic		
43a2	20.2	"	"			"				↓		
43b1	11.9	"	"			"			0	↓		
43b2	19.6	"	"			"			0	↓		
43b3	22.2	"	"			"			0	↓		
[illegible]2	10.5	"	"			"			0	parallel		

APHANITIC LIMESTONE ... continued

Sample No	Strength (MPa)	Diam (mm)	L/D	Velocity (m/secx10)^3	Density (g/cc)	Moisture (%) (lv/totlv)	Ox	Strain (%)	Time Submerged (days)	Orient to Bed	Fail Angle (°)	Load Rate (mm/min)
2 Brazilian Disk Tests:												
44a1	5.92	53.96	0.43			air dry			0	perpendicular		
51a2a	3.35	54.				saturated			28	parallel		
2 Fracture Toughness Tests:												
49a6b(x10)	2.5±0.40	25.	>2.0			air dry			0	parallel		
50BS1(x6)	6.5±1.8	25.	1.0						0	parallel		
2 Point Load Tests:												
GCOS1	2.5±0.40	41.	>2.0			air dry			0	parallel		
Beav Ck	0.82±.16	41.	>2.0						0			
1 Direct Shear Test:												
41a						saturated			1			
9 Direct Tension Tests:												
GCOS1T1	6.16	24.28	2.58		2.65	oven dry	1		0	perpendic		
GCOS1T2	5.83	24.27	2.55		2.65	.	1		0	↓		
GCOS1T3	4.4	24.27	2.72		2.64	.	1		0			
50a1a	8.84	25.10	2.99		2.56	.	1		0			
50a1b	2.4	25.08	2.97		2.52	.	2		0			
50a3	5.2	25.04	3.12		2.54	.	2		0			
50b1a	5.17	25.10	3.09		2.53	.	2					
50b1b	>6.9	25.10	3.00		2/.55	.	1		0			
50b2a	5.03	25.04	2.90		2.53	.	1		0	↓		
4 Bending Tension Tests:												
50a2a	[illegible]	25.14	6.2			ai[illegible]	1		0	parallel		
50a2b	[illegible]	25.09	6.05			.	1		0	↓		
51a1	16.4	25.14	5.9			.	1		0			
51b2b	14.7	25.16	6.3			.	1		0			

TEST RESULTS - NODULAR LIMESTONE

Sample No	Strength (MPa)	Diam (mm)	L/D	Velocity (m/secx10)	Density (g/cc)	Moisture (%) (Iv/totIw)	Qx	Strain (%)	Time Submerged (Days)	Orient to Beds	Angle (°)	Load Rate (mm/min)
10 Uniaxial Tests:												
Low-Clay:												
82a	75.6	54.08	2.07	4380	2.61	0.4	2	0.43	0	perpendic		0.10[illegible]
Medium-Clay:												
29c	47.7	41.12	2.10		2.6[illegible]	/1.7		0.40	[illegible]	↓		[illegible]
82b	37.8	54.06	2.03	3940	2.58	0.6/	4		0	↓		0.102
86a	46.5	74.99	2.03	3290	2.56		4	0.51	0	↓	85	0.203
92	43.5	75.21	1.96		2.52	/0.55		0.64		↓	90	0.102
110	40.8	54.04	1.89	3660	2.52	0.9/ 4		0.58	0	↓	70	0.203
High-Clay:												
81	48.[illegible]	75.30	1.94	3980	2.56	0.4/	3	0.45	0	↓	90	0.203
82d	40.9	54.00	2.13	3370	2.56	0.9/	5	0.52	0	↓		0.203
83	39.7	75.25	2.06	3780	2.56		5	0.55	0	↓	90	0.203
87a	42.3	75.05	2.06	3180	2.82		5	0.57	0	↓	90	0.203
8 Triaxial Tests:												
Medium-Clay, Saturated:												
46d	27.6/142.6	54.03	1.90		2.5[illegible]	/1.8	4	0.99	55	perpendic		0.203
High-Clay, Dry:												
2	29.0/182.7	41.16	2.10		2.55		5	1.0	[illegible]	↓		0.102
30a2	18.5/203 .8	41.22	2.12		2.56		5	0.62	[illegible]	↓	60	0.102
30a3	21.8/180.0	41.2	2.10		2.56	[illegible].25	5	0.68	0	↓	65	0.102
82c	4.0/ 80.5	54.00	2.03	3400	2.56	0.7/	4	0.36	0	↓		0.102
110b	7.5/112.6	54.07	1.89	3740	2.53	1.0/	5	0.[illegible]5	0	↓	70	0.102
111a	13.2/162.1	54.05	2.09	4370	2.56	0.8/	[illegible]		0	↓	65	0.102
3 Fracture Toughness Tests:												
3 (x[illegible])	6.1 ± 2.6	25.	1.0	very weathered nodular					0	perpendic		
33b(x8)	8.8 ± 1.7	25.	1.0	low-clay nodular					0	↓		
34 (x1)										↓		
105b(x4)	5.5 ± 1.7	25.	1.0	medium-clay nodular					0	↓		

NODULAR LIMESTONE ... continued

Sample No	Strength (MPa)	Diam (mm)	L/D	Velocity (m/secx10)	Density (g/cc)	Moisture (%) (Iv/totIv)	°Ox	Strain (%)	Time Submerged (days)	Orient to Bed	Fail Angle (°)	Load Rate (mm/min)
1 Point Load Test:												
Mtn1	field test conditions											
7 Direct Shear Tests:												
40b joint						saturated			1			
8 joint						saturated			1			
9/10*1 joint						saturated			1			
9/10*2 joint						saturated			1			
68*2 joint						saturated			1			
71a bedding						saturated			1			
73 bedding						saturated			1			
10 Slake Durability Tests:												
Low-Clay:												
33a	Is = 96%											
Syn1*227	Is = 90.4%											
Syn1*239	Is = 96.7%											
Syn2*258	Is = 95 %											
Medium-Clay:												
72	Is = 87.8%											
Mtn4	Is = 96.9%											
Mtn5	Is = 96.9%											
Mtn6	Is = 83.9%											
Very weathered Nodulare												
Syn1*225	Is = 44.9%											
Syn2*238	Is = 32.8%											

TEST RESULTS - D[illegible]SEMINATED ARGILLACEOUS [illegible]

Sample No	Strength (MPa)	Diam (mm)	L/D	Velocity (m/secx10)	Density (g/cc)	Moisture (%) (Iv/totIv)	Ox	Strain (%)	Time Submerged (days)	Orient to B[illegible]	Fail Angle (°)	Load Rate (mm/min)
8 Uniaxial Tests:												
21	54.[illegible]	74.98	1.82			air dry		0.68	0	perpendic		0.102
48c	34.[illegible]	75.31	1.99			air dry		0.91	0	↓		0.102
94a	[illegible]1.4	75.20	2.00		2.51	/0.66		0.74	0	↓		0.102
94b	67.0	75.21	2.03		2.51	/0.60		0.63	0	↓	75	0.102
94d	50.0	75.20	2.07		2.53	/0.60		0.69	0	↓	90	0.102
97a	54.[illegible]	75.05	2.04			/0.59		0.82	0	↓	88	0.102
98b	66.3	54.09	2.03		2.53	/0.31		0.58	0	↓	70	0.102
100f	6[illegible].[illegible]	53.72	1.96		2.53	/0.32		0.60	0	↓	80	0.102
											75	0.102
8 Triaxial Tests (dry):												
93a	29.0/163.5	54.04	[illegible].85		2.54			1.1	0	perpendic	65	0.102
98c.1	33.[illegible]/183.9	53.96	[illegible].99		2.5[illegible]			1.29	0	↓	65	0.102
98d	43.[illegible]/211.5	54.03	1.93		2.54			1.42	0	↓		0.102
100 b	[illegible].[illegible]/101.6	54.04	1.96		2.53			0.[illegible]0	0	↓	73	0.102
100 e	21.4[illegible]/158.2	54.07	2.00		2.54			[illegible]1	0	↓	68	0.102
101 a	11.3[illegible]/114.1	54.11	2.05		2.55			0.55	0	↓	7[illegible]	0.102
101 b	15.2[illegible]/139.7	54.06	2.05		2.54			0.71	0	↓	73	0.102
102 a	3.4[illegible]/82.	54.08	2.05		2.52			0.44	0	↓	72	0.102
1 Fracture Toughness Test:												
100c2 (x2)	4.5 + 0.11	25	1.0			air d[illegible]			0	perpendic		

-2 Slake Durability:

77a	Is = 88.9%
96a	Is = 88.9%

DISSEMINATED ARGILLACEOUS MICRITE ... continued

Sample No	Strength (MPa)	Diam (mm)	L/D	Velocity (m/secx10)	Density (g/cc)	Moisture (%) (Iv/totIv)	Qx	Strain (%)	Time Submerged (days)	Orient to Bed	Fail Angle (°)	Load Rate (mm/min)
27 Brazilian Tests:												
47a1a		54.00	0.39		2.54	air dry						
47a1b		53.90	0.36		2.54	air dry				parallel		
47a3	4.0	53.98	0.34		2.55				28			
51g1	3.3	41.17	0.49		2.52				28			
51g2	0.54	41.25	0.49		2.51				28			
93b1	4.76	53.86	0.49	3110	2.55				0			
93b2	1.79	54.00	0.45	3300	2.53		3		0			
93b3	3.38	53.73	0.46	3050	2.55				0			
94c2	4.79	53.67	0.47	2460	2.50				0			
94c3		53.76	0.45		2.53		3		9			
94c4		53.92							9			
95*1		54.00							9			
95*2		53.90							9			
95*3		54.00							9			
95*4	2.62	75.11	0.46		2.54	0.6/	3		28			
97b	5.0	74.92	0.45	3400	2.56		3		0			
98a	5.03	54.01	0.55	2360	2.54	2.0/	3		[illegible]			
98b	3.08	54.00	0.37						28			
98c2		54.01	0.46	2750	2.54	[illegible]	3		9			
100a1	4.79	75.18	0.44	2880	2.54		4					
100a8	4.14	75.18	0.42	3000	2.54	1.0/	3		0			
100d1	6.28	75.00	0.60	2920	2.55	>0.2/	4		0			
100d2	3.31	74.85	0.44	2760	2.54	>1.2/	3		0			
100g	3.27	74.92	0.57	3130	2.55		[illegible]					
100h1	4.72	54.00	0.48	3290	2.57	1.2/	3		0			
100h2	3.59	54.04	0.45	3360	2.57	1.0/	3		28			
100h3	4.76	54.08	0.37	2830	2.50		[illegible]					
ROC1	5.21	40.83	0.60		2.71		3					
ROC2		40.72	0.68		2.58		3		28			
ROC3		41.14	0.77		2.50		3		28			

TEST RESULTS - SHALY LIMESTONE

Sample No	Strength (MPa)	Diam (mm)	L/D	Velocity (m/secx10)	Density (g/cc)	Moisture (%) (Iv/totIv)	Qx	Strain (%)	Time Submerged (days)	Orient to Bed	Fail Angle (°)	Load Rate (mm/min)
5 Point Load Tests:												
Shaly Limestone:												
Mobia	2.3	50.	>2.0			field testing conditions				perpendic		
Mtnt												
Stony3	1.4	50.	>2.0									
Moderately Strong Argillaceous Limestone:												
Mtn3	3.0	50.	>2.0			field testing conditions						
Stony2(up)	2.3	50.	>2.0									
Mackay3	2.5	50.	>2.0									
1 Direct Shear:												
23a						saturated						
5 Slake Durability Tests:												
Banded Shaly Limestone:												
18	Is = 70.5%											
24a	Is = 92 %											
56a	Is = 49.6%											
60a	Is = 69.3%											
Shale:												
Syn2*242	Is = 23 %											
3 Swelling Tests:												
23c		75.	0.5			saturated				perpendic		
23d		75.	0.5			saturated						
59a		75.	0.5			saturated						

Thin Section Descriptions

Specimens Taken from WW1 Core.

#2. Unlaminated, blotchy; very weathered fabric. Yellowish with few fresh crystals. Cruddy; very even, regular fine granular. Some micrite under 50 microns and some micritic zones with crystals greater than 100 microns.

#10. Unlaminated and blotchy zones of limestone fragments. Some fossil fragments and remnant grains of calcite about 0.5 to 2mm. Matrix is extremely fine and fuzzy - a colorful mix of clays and calcite, with some scattered very angular quartz grains less than 50 microns, and with numerous very fresh opaque crystals.

#29b Large irregular zones and small nodular fragments of aphanitic crystalline, even textured limestone. Some sparry recrystallization, a few angular quart grains (120 microns); much clayey indistinguishable matrix.

#41h Rounded [illegible] nodules in a rusty, cruddy matrix. Matrix is [illegible] micrite with clays. Some coarse twinned calcites about 1mm.

#51d4 Poorly laminated, very fossiliferous with fragments up to 5mm (20%). About 5% sparite, some replacing fossils. Fine matrix is 80%; extremely fine calcite with clay, some fine fossil debris and fine sparite.

#86b Unlaminated and blotchy. No coarse fragments greater than 0.5mm. Matrix is a mass of 50 micron calcite and fossil fragments with much extremely fine calcite or clays. No sparite, rare quartz grains. Blotchy zones (nodules) are even textured aphanitic limestone

#101c Fossiliferous with much coarse sparite and very fine cruddy matrix. Fossil fragments are about 2mm, some very fibrous. Calcite crystals up to 0.5mm.

#105b Parly laminated; remnant fossil forms about 2mm are recognizable (10%). Some brilliant sparry crystals about 0.5mm are twinned. Matrix is cruddy clays with micrite less than 100 microns.

NODULAR LIMESTONE ... continued

Sample No	Strength (MPa)	Diam (mm)	L/D	Velocity (m/secx10)	Density (g/cc)	Moisture (%) (lv/totlv)	[illegible]	Strain (%)	Time Submerged (days)	Orient to Bed	Fail Angle (°)	Load Rate (mm/min)
27 Brazilian Tests:												
35*1	5.13	54.05	0.42		2.58				28	parallel		
35*2	2.87	54.03	0.51		2.57				28			
35*3	3.38	54.03	0.51		2.55				28			
35*4	1.38	54.00	0.43		2.55				28			
46a1	2.93	54.03	0.44		2.57							
109b	4.07	75.30	0.51		2.54				0			
28b1	4.17	41.10	0.59		2.55				28			
28b2	7.21	41.15	0.66		2.60				28			
29a1	3.97	41.12	0.67		2.61				28			
29a2	3.86	40.99	0.68		2.61				28			
29b1	5.55	41.12	0.66		2.62				28			
29b2	4.02	41.18	0.64		2.59				28			
40a1	4.19	54.01	0.58									
40a3	2.28	54.00	0.38		2.41				28			
46a2	2.76	54.03	0.39		2.57				28			
46a3	2.93	54.00	0.43		2.57				[illegible]			
46a4	2.59	54.00	0.56		2.58				[illegible]			
46b	4.59	53.98	0.37		[illegible]				[illegible]			
46c1	3.52	54.00	0.47		[illegible]				[illegible]			
46c2	3.46	54.00	0.48		[illegible]				[illegible]			
46c3	2.26	54.03	0.45		2.57				[illegible]			
86b	3.93	41.01	0.64	3810	2.56				[illegible]			
103	2.93	54.05	0.71	2900	2.52	1.2/			0			
105a1	4.07	54.08	0.51	3480	2.49		3		0			
87ba	4.21	75.12	0.46	3470	2.56	0.8/	4		0			
87b2	1.79	74.84	0.48	2420	2.55		4		0			
87b3	3.38	74.96	0.47	3420	2.55	0.9/	5		0	↓		
8 Double Shear (med- to high-clay Nodular):												
46b	14.83		>1.5			air dry			0	perpendic		
47b	9.59		>1.5						0			
64*1	15.21		>1.5						0			
64*2	21.03		>1.5						0	↓		
68a	9.52		>1.5						0			
68b	8.76		>1.5						0	parallel		
68*1	8.28		>1.5						0			
68*1b	17.10		>1.5						0	↓		