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# ESTIMATES OF MAXIMUM PAST OVERBURDEN FOR THE PIERRE SHALE, HAYES AREA, SOUTH DAKOTA

By

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# ABSTRACT

The Pierre Shale of the Northern Great Plains area of the United State is an Upper Cretaceous shale which was deposited in a marine environment. Geotechnically, the shale has been classified as an overconsolidated clay-shale. In South Dakota the Pierre Shale crops out extensively in the central and western portions of the state.

In this study an investigation was conducted for the purpose of clarifying and examining the existence of a discrepancy between geotechnically and geologically derived estimates of maximum past overburden for the Pierre Shale at Hayes, South Dakota.

The geological determination involved examining the topographic high points of central South Dakota for the purpose of locating the remnants of any Tertiary rock that may have existed in the area. Based on this field evidence, a geologic profile showing estimated thickness of former strata in the area was constructed and the maximum thickness of past overburden was estimated for the Hayes study site.

The geotechnical determination was made by conducting laboratory high-pressure consolidation tests on samples from cores from Hayes. Preconsolidation pressures were estimated from the consolidation curves and the values were converted to thickness of overburden.

The geological determination of the maximum thickness of past overburden indicates that 600 to 1100 feet (183 to 335 m) of Tertiary rock and Cretaceous Pierre Shale has been removed by erosion at the Hayes site. Geotechnically, the preconsolidation pressures indicate that 3600 to 5000 feet (1100 to 1525 m) of material has been removed. The discrepancy that exists between the geological and geotechnical determinations is considered significant.

Because it was believed the geotechnical estimate was too high instead of the geological too low, the search for the cause of the discrepancy centered on those factors known to affect the determination of the preconsolidation pressure, $P_c$.

Laboratory factors were ruled out because their affect is to reduce the estimated $P_c$, thus reducing the discrepancy. Of the geological factors that are known to increase $P_c$, only two warranted assessment in this study — cementation and delayed consolidation. By default, these two mechanisms appear to be the possible causes for the discrepancy.

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# ACKNOWLEDGEMENTS

For her patience, I thank my wife, Melissa.

And, for helping me keep things in proper perspective, I thank my son Keith.

Thomas L. Rice

# 1. REPORT INTRODUCTION

## 1.1 The General Problem

Past work by this author and other investigators indicated that for certain geologic materials significant discrepancies exist between the geotechnically and the geologically derived estimates of maximum past overburden.

Maximum past overburden refers to the greatest thickness of sediment that has ever overlain a particular point in a sedimentary sequence. Estimates of maximum past overburden are generally derived from either "geologic evidence" or "geotechnically determined preconsolidation pressures."

Theoretically, if all factors are taken into account, preconsolidation pressures can be converted to accurate overburden thicknesses, and vice versa. Rarely, though, can all factors be taken into account. Thus, in some cases the geotechnically determined preconsolidation pressures indicate the amount of overburden material necessary to achieve the present degree of consolidation is less than what the geologic evidence indicates was present; and, in other cases the exact opposite situation occurs — the preconsolidation pressures are too high to be attributed to the geologically determined amount of maximum past overburden (Spangler and Handy, 1982).

It needs to be recognized that, here, "geologic evidence" refers only to field-identifiable thicknesses of overburden material, past and/or present; and, "geotechnically determined preconsolidation pressures" are determined by laboratory consolidation tests conducted and interpreted in accordance with conventional geotechnical engineering practice.

When a discrepancy as described above occurs, a search for the missing, or misunderstood, factor(s) can be made. The unaccounted-for factors responsible for a discrepancy may include geologic factors as well as factors that are not properly simulated in conventional laboratory consolidation tests. In the past it has been shown that for the cases where the preconsolidation pressures appear to be too low for what the geologic evidence infers, the discrepancy could be attributed to either sample disturbance or the possibility that the material was only recently deposited. In the situation where the preconsolidation pressures are higher than inferred by the geologic evidence, numerous mechanisms have been described to help explain why the discrepancy occurs. Among these mechanisms are time-dependent delayed consolidation and cementation.

This study identifies and characterizes a maximum-past-overburden discrepancy in a particular geologic material and then examines the extent to which the previously mentioned factors and mechanisms could have caused that discrepancy.

## 1.2 The Specific Problem

A specific example of a material for which the preconsolidation pressures appear to be too high for the field-identifiable amount of maximum past overburden is the Pierre Shale.

The Pierre Shale is a Late Cretaceous deposit derived primarily from clays and silts which settled to the bottom of a broad epeiric sea that covered what is now the Great Plains states and contiguous areas to the west and north (into Canada). In the United States the major areas of exposure of the Pierre Shale are in north-central Montana and in central South Dakota where the strata are generally flat lying and have broad areas of outcrop.

Existing evidence concerning a discrepancy between geologic and geotechnical estimates of maximum past overburden for the Pierre Shale consists primarily of that presented in studies by Fleming, Spencer, and Banks (1970) and McKown and Ladd (1982). Fleming's study

examined the situation for a location within the Missouri River trench in central South Dakota while McKown's investigation focused on the problem at a site in northeast Nebraska, again within the Missouri River trench.

In 1982 this author had the opportunity to obtain core samples of the Pierre Shale from a U.S. Geological Survey (USGS) drill site in central South Dakota located several miles west of the Missouri River trench. At the same time the opportunity also existed for this author to develop for the USGS a laboratory apparatus which, as one of its capabilities, could be used to conduct high-pressure one-dimensional consolidation tests on stiff shale material.

The U.S. Army Corps of Engineers a few years earlier had conducted high-pressure one-dimensional consolidation tests for the USGS on Pierre Shale core samples which came from the same area as the 1982 USGS cores. Nothing related to maximum past overburden had been done with this data until this author interpreted and used it in this study.

During the summers of 1983 and 1984 a geologic field investigation was conducted by this author in central South Dakota for the purpose of gathering data for use in

examining the problem this study addresses, namely the comparison of geotechnically and geologically derived estimates of maximum past overburden in the Pierre Shale.

## 1.3 Purpose of Study

The purpose of this study was to examine a suspected discrepancy between geotechnically and geologically derived estimates of maximum past overburden for the Pierre Shale in the Hayes area of central South Dakota. More specificially, the purpose was to clarify the nature and magnitude of the discrepancy, including its variation with depth, and to identify and evaluate the possible causes of the discrepancy.

## 1.4 Scope of Study

The study had five major components to it which, in essence, reflect the scope of the study. They were:

1. Developing a high-pressure consolidometer for performing one-dimensional consolidation tests on clay-shale samples;
2. Performing one-dimensional consolidation tests on Pierre Shale samples obtained by the U.S. Geological Survey during a 1982 drilling program conducted near Hayes, South Dakota;

3. Examining and interpreting the data from one-dimensional consolidation tests that were performed by the U.S. Army Corps of Engineers on Pierre Shale samples obtained by the U.S. Geological Survey during a 1978 drilling program conducted near Hayes, South Dakota,
4. Conducting geological field investigations in central South Dakota in an area surrounding Hayes; and
5. Assimilating the field, laboratory, and previous-studies information in order to be able to achieve the goals set forth for this study.

## 1.5 Study-Site Location Description

The study area is located in Stanley and Haakon Counties in central South Dakota. The community of Hayes in Stanley County is situated in the middle of the area and is located 32 miles (52 km) due west of the state capitol, Pierre. A precise delineation of a boundary for the study area was not practical from a geological standpoint; for purposes of reference, however, a circle with Hayes as the centerpoint and having a radius of approximately ten miles defined a "study area." This area is located atop a broad plateau bounded by the Bad River drainage on the south, the Missouri River trench on

the east, and the Cheyenne River drainage on the north and west (Figure 1).

Central South Dakota belongs in the physiographic province known as the Great Plains. The Great Plains province is made up of many sections, each with its own geomorphic characteristics. The study area is located in the Missouri Plateau section of the Great Plains and, specifically, in the unglaciated portion of the Missouri Plateau where erosion of the extensive surface exposure of the Pierre Shale has produced the Pierre Hills. The Pierre Hills physical division is characterized by mature topography of low rolling hills and a well-integrated drainage system. Downcutting by the Missouri River has rejuvenated the drainage system, and steep-walled youthful valleys now are encroaching on the rolling uplands (Erskine, 1973). Local elevation relief in the study area is less than 500 feet (152 m).

The Pierre Shale cores which were studied as a part of this maximum-past-overburden investigation came from two USGS sites located within two miles (3.2 km) of each other along U.S. Route 14 in Stanley County. The two drill sites were given the identifying designations H2 and H12. H2 was drilled in the summer of 1978 and was situated west of Hayes at an elevation of approximately 2030 feet. H12 was drilled in the summer of 1982 and was

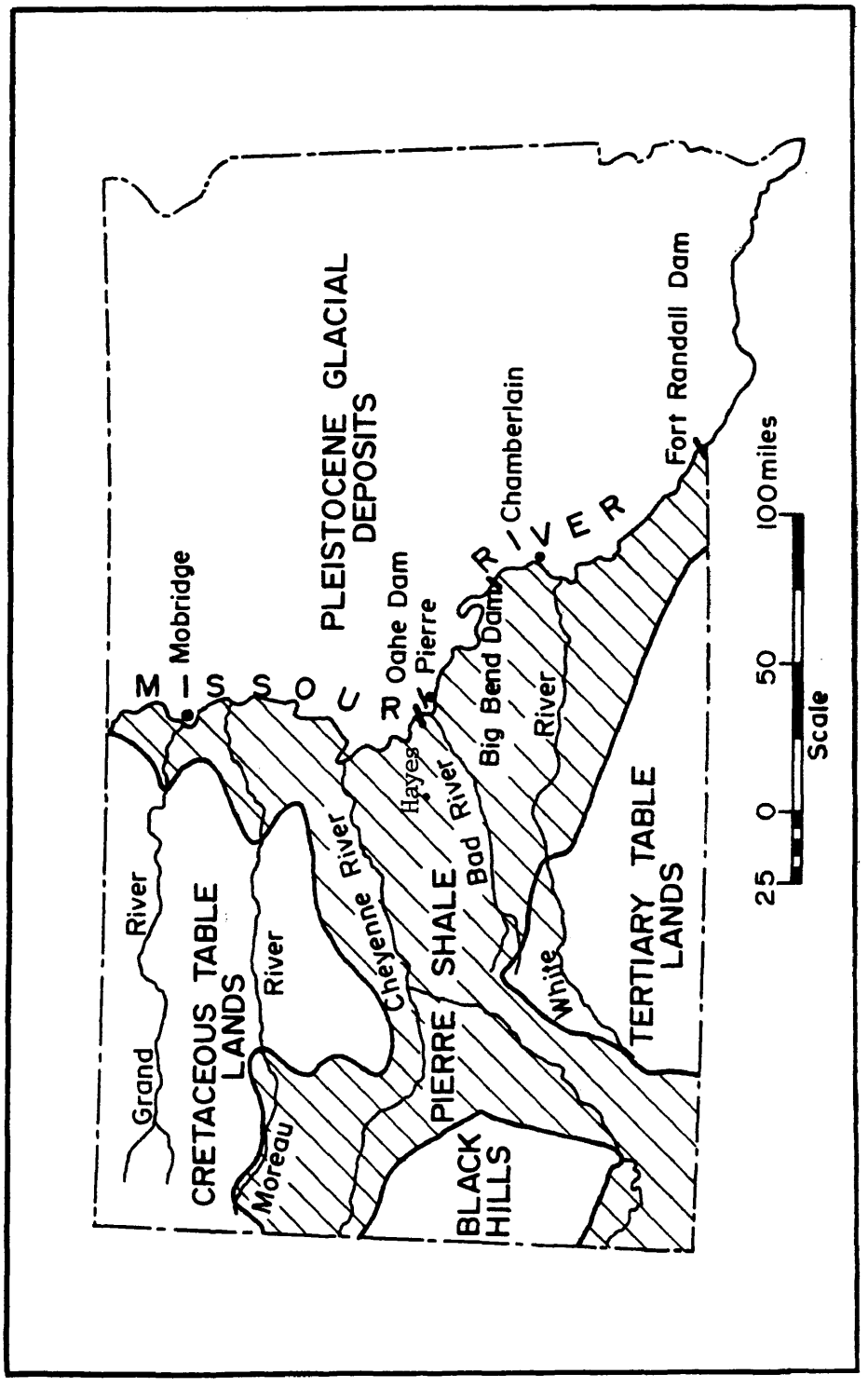



Figure 1 - GENERAL GEOLOGY OF SOUTH DAKOTA.
(From Scully, 1973)

situated in east Hayes at an elevation of approximately 2080 feet. Both sites were drilled using an air drilling (rotary) technique. The holes went to depths of almost 600 feet (183 m). The Pierre Shale sequence is approximately 1000 feet (305 m) thick at these locations.

## 1.6 Overview of Previous Studies

Past work in the Pierre Shale of South Dakota falls primarily into one of three categories — "pure" geologic studies, dam construction on the Missouri River, or slope stability investigations (other than those related to dam construction). Current studies in the Pierre Shale relate to hazardous waste repository site investigations and highway construction and maintenance issues.

"Pure" geologic studies of the Pierre Shale in South Dakota are not as numerous as one might suspect. The account of the geologic history of central South Dakota that is referenced most often is that by D. R. Crandell (1958). Others have discussed the geologic setting of the Pierre Shale in a more regional context (Tourtelot, 1962; Gill and Cobban, 1961, 1973; Schultz, 1965; Schultz and others, 1980). The Pleistocene geology of eastern South Dakota was examined in detail by R. F. Flint

(1955), while Crandell (1953) studied the Pleistocene in the central part of the state.

The number of investigators who directly addressed the issue of maximum past overburden of the Pierre Shale in South Dakota is quite small. The study by Fleming, Spencer and Banks (1970) is the only significant one that can be referenced when geologically versus geotechnically derived estimates are discussed.

Currently, numerous USGS researchers are examining various aspects of the Pierre Shale in South Dakota. Included are T. C. Nichols (engineering characterization), D. S. Collins (geology), K. E. Kolm, A. F. Chleborad, and G. W. Shurr (tectonics), C. E. Neuzil (groundwater flow), and H. W. Olsen (chemical osmosis). See Reference List.

# 2. GEOLOGICAL DETERMINATION OF MAXIMUM PAST OVERBURDEN

## 2.1 Techniques for Making Geological Determination

In an attempt to determine the thickness of overburden eroded away in central South Dakota at the Hayes study area, field work for this study was conducted by this author during the summers of 1983 and 1984 for the purpose of finding remnants (float or in situ) of Cenozoic (particularly Tertiary) material that may have existed in the area.

In order to evaluate whether or not the material found in the field was Tertiary in age, a working knowledge about the geology of the Pierre Shale (Mesozoic in age) was required. More specifically, it was important to be able to identify in which member of the Pierre Shale certain surface locations existed.

Numerous Pierre Shale and "non-Pierre Shale" sites in central South Dakota were visited where surface samples of rocks and fossils were examined. Based primarily on previously reported ages of similar materials from nearby locations, age determinations for the various sites were made. A straight-line schematic geologic profile was constructed using the field data of this study along with information from other investi-

gators. The Pierre Shale section encountered at drill site H12 was fitted into the profile and an estimate was made of the amount of Pierre Shale and Tertiary deposits that had been eroded away from the Hayes study area.

## 2.2 Cenozoic History of Western South Dakota

In Late Cretaceous time western South Dakota was covered by a large inland sea. In ascending order the formations which represent this period of time are the Graneros Shale, Greenhorn Limestone, Carlile Shale, Niobrara Chalk, Pierre Shale, and Fox Hills Sandstone. The Pierre Shale and Fox Hills Sandstone belong to the Montana Group of formations while the remaining (lower) formations belong to the Colorado Group. The Fox Hills represents the last marine deposit of the Cretaceous; however, it does not represent the end of Cretaceous deposition in South Dakota. The uppermost Cretaceous beds are contained in the Hell Creek Formation, a swamp and brackish-water type of deposit.

As the Cretaceous period was drawing to a close a general uplift was taking place in the areas that were to become the Black Hills and Rocky Mountains. The large inland sea, which had been a catch basin for sediment for

millions of years, was greatly reduced in size, and only isolated deeper-water or down-warped areas continued to receive sediment like before. Other areas that had previously been underwater were lifted above base level and erosion of the Cretaceous formations began (Harksen and Macdonald, 1969).

During the Paleocene Epoch, parts of western South Dakota were receiving sediments while other areas were having Cretaceous material eroded away. There is little evidence of Eocene deposition. In one county in the northwestern part of the state two stratigraphic units have been referred to the Eocene. These two units are very limited in extent and are the only remnants of the more than 20 million years of the Eocene epoch. Harksen and Macdonald state that "undoubtedly there was a tremendous amount of deposition, evolution, and erosion that took place in South Dakota during this time — but at present we can do little more than infer the history from what is known of adjacent regions."

Others have stated a somewhat different opinion. Trimble (1980) simply calls the last half of the Eocene in the Great Plains region "a long period of stability...when there was little uplift of the mountains and, therefore, little deposition on the

plains. A widespread and strongly developed soil formed over much of the Great Plains during this period of stability." According to Harksen and Macdonald, however, "weathering, soil formation, and erosion continued at a rapid rate [during the Eocene] with erosion probably stripping away the soil as fast as it was formed."

The two opinions stated above are not necessarily as contradictory as they may first seem. The fact is, though, that no direct evidence has been uncovered to date which reveals what happened geologically in South Dakota during the Eocene.

The only reason for dwelling on the Eocene in this report is because knowledge about Eocene deposits, or the lack of them, could help resolve to some degree any discrepancies that are shown to exist between geotechnically and geologically determined amounts of past overburden of the Pierre Shale.

With regard to the Oligocene, Miocene, and Pliocene epochs — deposition (and occasional erosion) in South Dakota is known to have occurred during these times. However, the exact thickness of these westerly derived, terrestrial, wind and waterborne deposits is not known for large areas of central South Dakota. Figure 2 shows

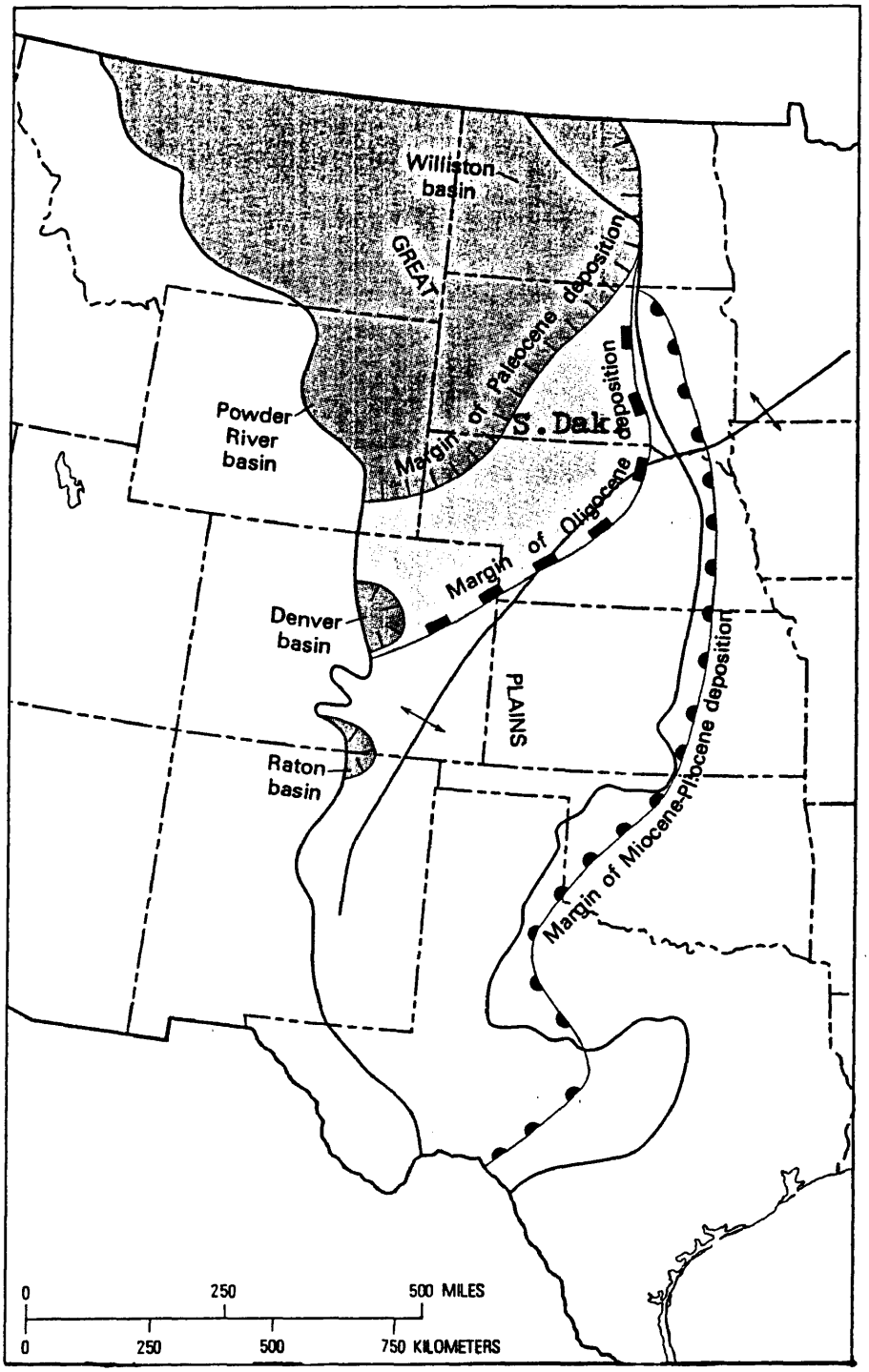



Figure 2 - PROGRESSIVE SOUTHEASTWARD EXPANSION OF AREAS COVERED BY PALEOCENE, OLIGOCENE, AND MIOCENE-PLIOCENE SEDIMENTARY DEPOSITS (from Trimble, 1980).

the approximate extent of the various Tertiary deposits on the Great Plains region of the United States.

In western South Dakota during the Tertiary, periods of erosion were interspersed with periods of deposition; however, the main geological factor was deposition. During the Pliocene Epoch the land surface from Texas northward through South Dakota was buried beneath a "flood" of sediments (mostly poorly-consolidated sand). These alluvial sediments, which came from the Rocky Mountains and Black Hills in the west, were sometimes several hundred feet thick. Using a moderate amount of evidence and a vast amount of logic, most researchers have concluded that the depositional units thinned substantially towards the east away from the source area. Investigators who studied this "Tertiary grit" in the late 1800's named the formation the Ogallala. The geologists who studied the Ogallala in western South Dakota, however, did not find much of this Tertiary sediment left to examine. In late Pliocene time erosion removed much of the Ogallala in South Dakota, leaving only small isolated remnants of what once was "a very flat area of very low gradient which stretched as a gently sloping plain" for thousands of square miles (Harksen and Macdonald, 1969).

The Missouri Valley in central South Dakota was formed during the Pleistocene Epoch and its development coincides approximately with the furthest southwestern advance of glaciation. Although glaciers did extend into Stanley County to a point close to the study area (Flint, 1955; Crandell, 1953, 1958) there is no evidence that they actually reached the Hayes area.

The Pleistocene was, and the Holocene has been, predominantly, a time of erosion in western and central South Dakota. Five rivers, the Grand, Moreau, Cheyenne, Bad and White Rivers flow into the Missouri River from the west. Prior to the glacial period these rivers flowed beyond the present Missouri Valley to the east. The Missouri formed in older northwest and southeast drainages by eroding the shale and other deposits in the existing drainage divides, thus creating a continous valley. Much of the drainage system west of the river existed prior to the formation of the Missouri itself (Scully, 1973).

It is speculated by Harksen and Macdonald, that at certain times during the Pleistocene, great amounts of coarse materials were carried far out onto the plains by streams that had been turned into "raging torrents." The existence of Pleistocene age, stream-derived, sand

and gravel deposits of western provenance in central South Dakota is well documented (Crandell, 1958, among others). These "raging torrents" coincided with periods of glacial advance and ceased to exist during interglacial stages. When the advance of glaciation in eastern South Dakota ended and precipitation conditions returned to normal in western South Dakota, the stream valleys were choked with coarse sediments. Because the Tertiary rock was more easily eroded than the valley fillings, the streams eroded the Tertiary rock and left the gravel behind. Continued erosion brought about a topographic reversal which left gravel capping the interfluves (Harksen and Macdonald, 1969). Evidence of this topographic reversal was found by this author in various locations near the Hayes study area.

## 2.3 Geologic Data and Maximum-Past-Overburden Values

Previous geological investigations that addressed the subject of deposits younger than the Pierre Shale, in areas where the Pierre is now the surface material, quite often relied on assumptions and inferences in order to be able to claim that Tertiary deposits had overlain the Pierre formation. An example of some of the conclusions and how they were reached are presented here in the form

of quotes from those investigators who discussed the Tertiary geology of South Dakota. It is not necessary at this time for the reader to know exactly the location of the specific sites (buttes, etc.) that are mentioned; the technique employed for determining the existence of Tertiary deposits should still be apparent.

> "Beds have been found in the Ree Hills which...may belong to...the Tertiary... It seems not improbable that the same formation occurs in Medicine Knoll... Various conspicuous buttes west of the Missouri to the north and east of the continuous Tertiary beds doubtless contain the same formation..." From Todd, 1894, p.110.

> "There is but little doubt that the Bijou Hills, 2000 feet above sea-level in the southern part of Brule County, east of the Missouri River, are but remnants of the common surface that at one time stretched over all the southern portion of South Dakota. The Bijou Hills are doubtless remnants of the bluff hills that overlooked the pre-glacial White River as it flowed on to the east into the old Missouri River." From Perisho, 1908, p.105.

> "In a few places the Pierre hills region is surmounted by isolated buttes standing as much as 400 feet above the general surface and visible from distances of many miles. Examples are the Iona Hills in Tripp, Gregory, and Brule Counties, and Medicine Butte in Lyman County. These buttes are capped by Tertiary strata such as form the plateaus farther south. The caps show that such strata extended over much if not all of the Pierre hills region, and that they have been removed largely by undermining the

> weak underlying shales." Further, "The vertical distance between the tops of the Iona Hills and the Missouri River is more than 800 feet. This is a minimum measure of the extent to which the country immediately west of the river has been incised since Ogallala time. And since the Iona Hills and Medicine Butte capped by the Ogallala formation stand some 300 feet above the general surface of the interfluves, a prism of rock about 300 feet thick must have been removed from that country completely." From Flint, 1955.

Flint's report of 1955 contains a number of maps which pinpoint the locations of Pierre Shale, Fox Hills Sandstone, Hell Creek sediments, and Ogallala sediments in eastern South Dakota.

The Ogallala Formation is of primary importance in this study because remnants of it are probably the most easily identifiable material remaining from the Tertiary beds.

According to Erskine (1973),

> "The Ogallala formation of Pliocene age is a heterogeneous mixture of silt, sand and fine to medium gravel locally cemented to form orthoquartzite.... Uplands and buttes protected by resistant caps of orthoquartzite of the Ogallala rise above the general land surface... The original thickness of the formation is unknown and the present thickness varies because of erosion. The average thickness in the area [south-central South Dakota] is about 40 feet... The orthoquartzite is grayish olive in fresh exposures and weathers to yellowish gray. Unconsolidated parts of the formation generally are pale shades of gray."

This description of an olive or greenish orthoquartzite is pervasive throughout the literature where discussions of the Ogallala Formation are found. Crandell mentions finding it at various locations in the area covered in his 1958 report; however, he found no bedded green quartzite, only pieces varying in size and angularity. In the cases described by Flint (1955), Winchester and others (1916), and Stevenson (see Agnew and Tychsen, 1965), the green quartzite occurs as in situ material or very large butte-capping blocks. Flint's and Stevenson's descriptions are for quartzite that caps buttes in south-central and southeastern South Dakota, while Winchester's description is for a green quartzite in northwestern South Dakota.

Various facies names or "sub-formation" names have been given to the greenish, orthoquartzitic, Tertiary material that is found in South Dakota and surrounding states. None of these names will be used in this report; instead, the deposits will simply be referred to as a lower-Ogallala deposit. The age of the Ogallala is not known precisely, but based on a review of the literature the concensus seems to be that it falls approximately at the Miocene-Pliocene boundary. Since the greenish quartzite is in the lower part of the

Ogallala, the quartzite will be considered to be late Miocene in age. It should be noted that the quartzite, at its base, is conglomeratic and contains rounded, green, clay (shale) pebbles.

In south-central South Dakota the quartzite facies of the Ogallala varies in thickness from 38 to 54 feet (12 to 16 m) (Stevenson, 1953 in Agnew and Tychsen, 1965). The total thickness of the Ogallala sediments in the same area may have been more than 300 feet (92 m).

Before discussing the data used for reconstructing the amount of past overburden at the Hayes study area, a final quote will be given from another investigator who attempted to make the same kind of determination in a different part of South Dakota.

> "The preconsolidation load imposed by sediments at all the sites was estimated from available geologic and topographic maps by determining the youngest nearby formations present either as isolated erosional remnants or as down-faulted blocks. The thicknesses of the formations that appear to have been removed were projected to the study sites and the load estimated. The results are highly speculative, but they do provide a general indication of the geologic preconsolidation load." From Fleming and others, 1970.

Basically, a similar method which relied on field work instead of map work was used in this study to reconstruct the thicknesses of the formations that once covered the Hayes, South Dakota area. This method does not adequately take into account the maximum thickness that any single-age deposit may have attained. Most of the rock units lay unconformably on top of one another and it is probable that the maximum thickness of any single unit was more than the amount still present for that unit. However, it is assumed here for convenience that the total original thickness of any single rock unit was never any greater than the combined present-day thicknesses of the rock units, as indicated by the isolated erosional remnants (i.e., buttes).

If indeed core H12 at Hayes was situated in the Pierre Shale sequence in the manner believed, then the surface material at Hayes is in the lower part of the Elk Butte Member of the shale. The Elk Butte is the uppermost member of the Pierre Shale.

Based on information from Crandell (1958), Schultz and others (1980), and Erskine (1973), among others, the amount of Elk Butte that has been eroded away from the site is 100 to 200 feet (30 to 61 m). By combining this amount of eroded Elk Butte with the thickness of the

material that should have existed between the top of the Pierre Shale and the top of the green quartzite unit of the Ogallala, it is estimated that a minimum thickness of 600 feet (183 m) has been removed above a reference elevation of 2100 feet at the Hayes study site (Figure 3). This would be a minimum thickness because, as shown on the geologic profile, no bedded material younger than the green quartzite was found during the field work of this study.

The four pages following Figure 3 (Figure 3 Comments, Figure 4, Table 1, and Figure 5) present the evidence or information used in the construction of the geologic profile of Figure 3.

The more likely thickness of removed overburden at the Hayes site is greater than 1000 feet (305 m). This is based on the fact that other areas to the northwest and south-southeast clearly indicate that additional material was, in fact, deposited on top of a (olive) quartzite unit of Miocene-Pliocene age (Flint, 1955; Winchester and others, 1916). Also, it is hard to imagine a sand unit being diagenetically altered to a sandstone or ortho-quartzite while remaining a surficial deposit.

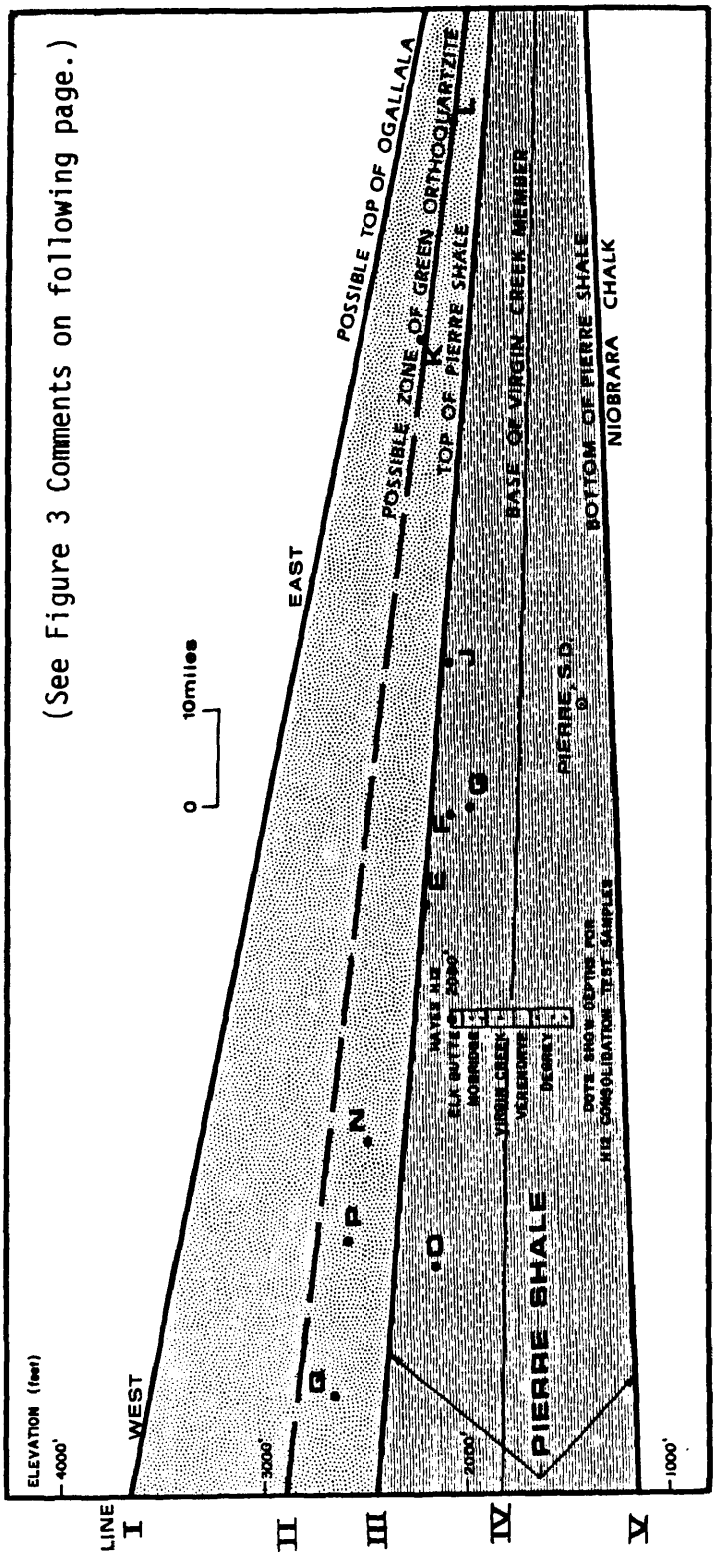



Figure 3 - BEST-FIT, STRAIGHT-LINE SCHEMATIC GEOLOGIC PROFILE FOR USE IN THE GEOLOGICAL DETERMINATION OF MAXIMUM THICKNESS OF PAST OVERBURDEN IN CENTRAL SOUTH DAKOTA.

## FIGURE 3 COMMENTS

The following comments apply to Figure 3 (the geologic profile) on the previous page:

1. The profile shows a simplified reconstructed geologic section for an east-west trending line that passes through Hayes and Pierre, South Dakota.

2. The ratio of the horizontal scale to the vertical scale is 105.6.

3. The letters match those on Figure 4 and in Table 1.

4. Sample depths (dots) on the H12 core "profile" occur at 96', 159', 232', 412', 502', and 564'. Three of the five encountered members were represented.

5. In descending order, the members of the Pierre Shale are: Elk Butte, Mobridge, Virgin Creek, Verendrye, DeGrey, Crow Creek, Gregory, and Sharon Springs. The bottom three members were not encountered in the drilling of H12.

6. Line I is based on the paleotopographic map of Harksen and Macdonald (1969). See Figure 5 of this report.

7. Line II is solid where control exists, dashed where control does not exist. It could possibly be shown at a little higher elevation in the west.

8. The formation between lines I and II would be entirely Ogallala.

9. The formations between lines II and III would include the Fox Hills, Hell Creek, and possibly some sediments left from the early Tertiary (Oligocene?).

10. Surface elevations for the lettered sites were obtained from USGS topographic maps.

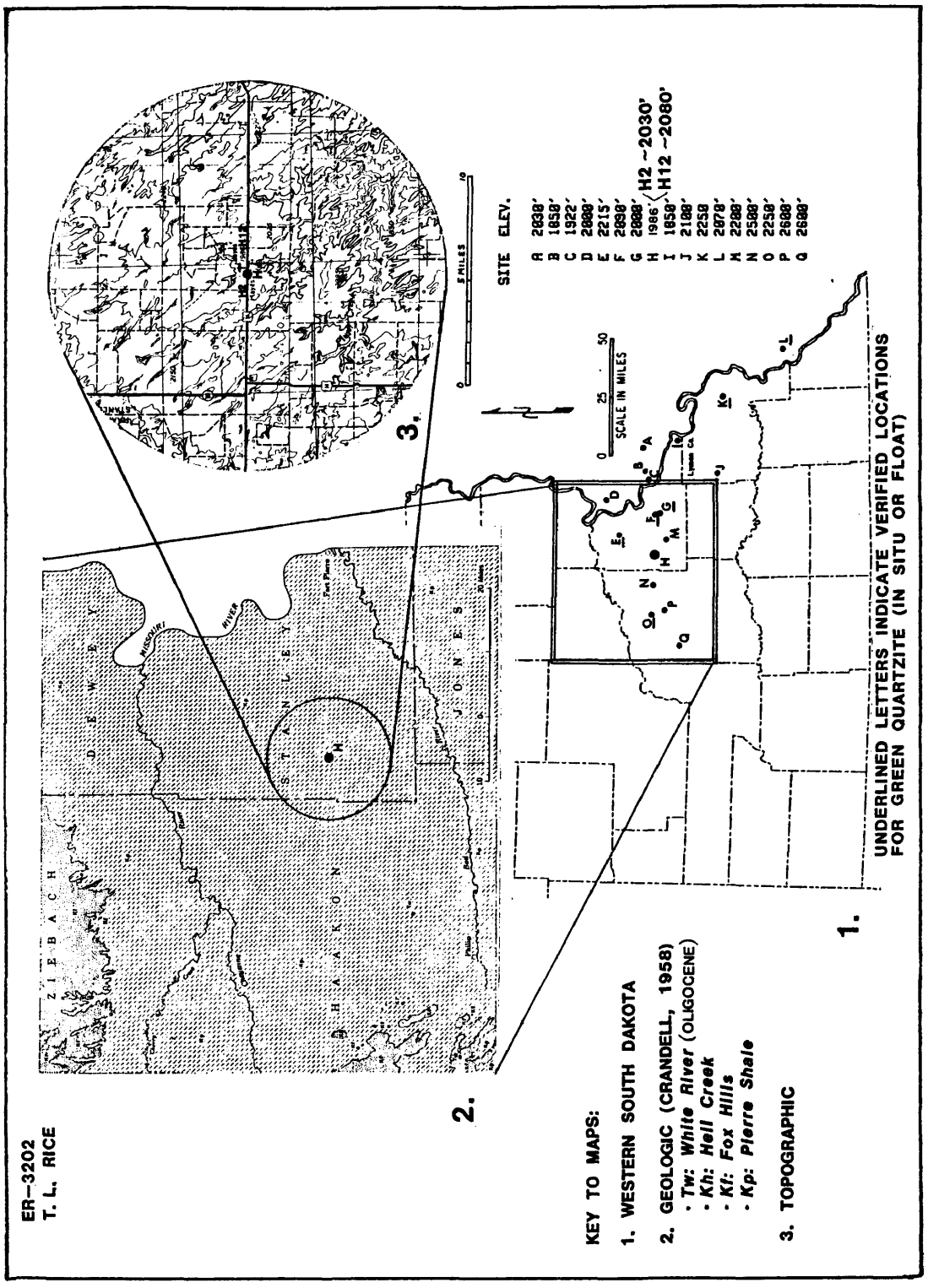



Figure 4 - STUDY-AREA LOCATION MAP SHOWING SAMPLING SITES.

TABLE 1 - Surficial Sampling Sites for This Study in Central South Dakota

| SITE (letters match those on Figure 3 and Figure 4) | NAME | ELEVATION (ft) (above sea level) | GREEN QUARTZITE (in situ or float) | EVIDENCE FOR "CONTROL" POINTS ON FIG. 3 PROFILE |
|---|---|---|---|---|
| A | Medicine Knoll | 2030 | ----- | ------ |
| B | Gravel Pits | >1850 | ----- | ------ |
| C | Snake Butte | 1922 | ----- | ------ |
| D | Sully Butte | >2000 | ----- | ------ |
| E | Standing Buttes | 2215 | Float | small, rounded, green arenaceous "pebbles" |
| F | Willow Creek Butte | 2090 | Float | pieces of subangular greenish quartzite |
| G | Stroup Locality | 2000 | Float | green quartzite known (Crandell, 1958) |
| H | Hayes, South Dakota | 1986 | ----- | geologic logging of Core H12 |
| I | Ft. Georges Buttes | 1850 | ----- | ------ |
| J | Vivian-Rt. 83 Roadcut | >2100 | ----- | Upper-Pierre or Fox Hill ammonites known (Crandell, 1958) |
| K | Medicine Butte | 2250 | Float | large angular blocks of greenish quartzite |
| L | Bijou Hills | 2070 | In situ | butte-capping greenish quartzite |
| M | Doty Ridge | 2200 | ----- | ------ |
| N | Hilltop Ranch | >2500 | ----- | numerous shallow-marine clams |
| O | Ferguson Ranch | 2250 | Float | angular piece of greenish quartzite; Upper-Pierre baculites |
| P | Hansen Ranch | 2600 | ----- | numerous shallow-marine clams |
| Q | Grindstone Butte | >2600 | ----- | sandstone; of presumed Fox Hills age |

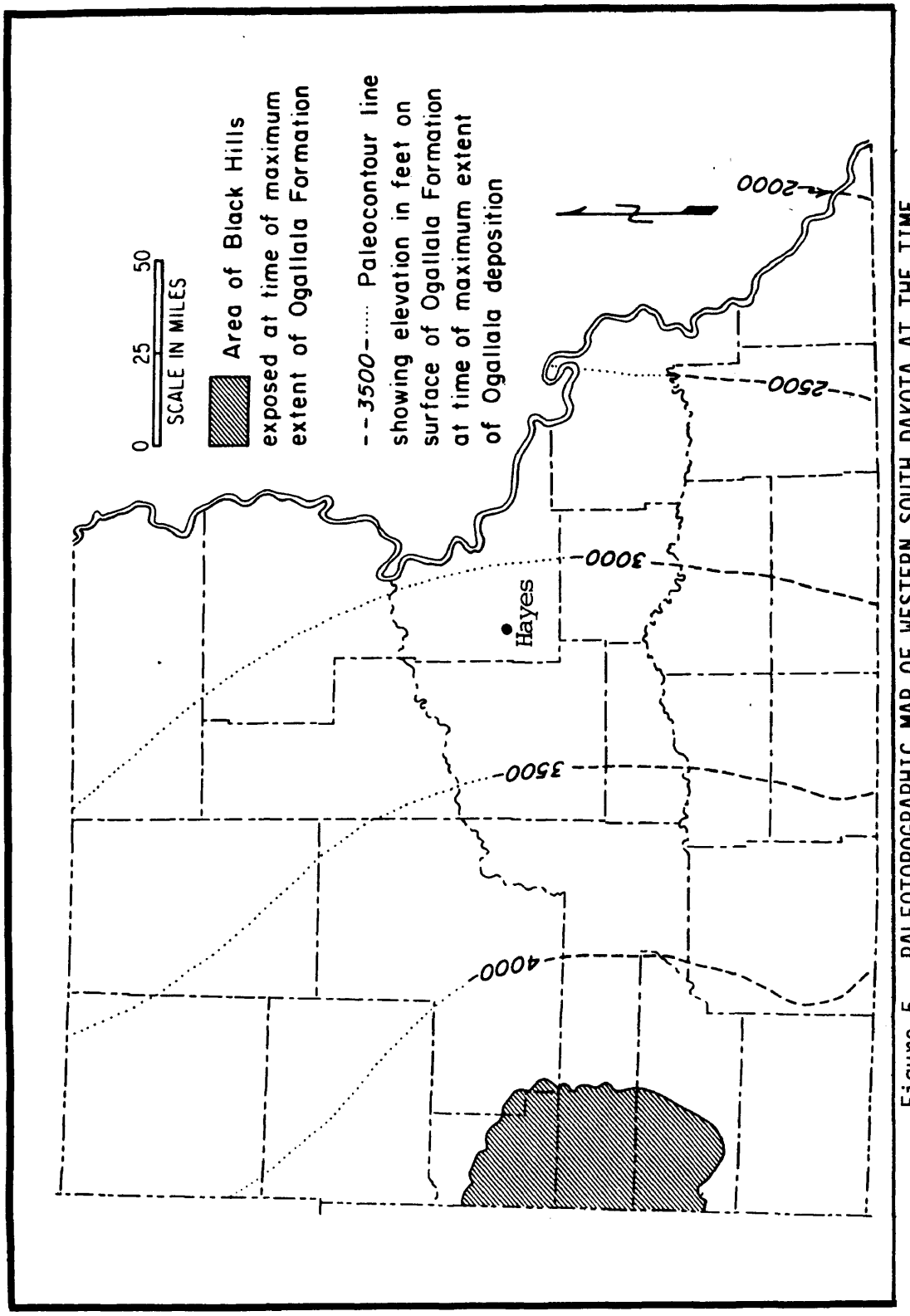



Figure 5 - PALEOTOPOGRAPHIC MAP OF WESTERN SOUTH DAKOTA AT THE TIME OF MAXIMUM OGALLALA DEPOSITION. CONTOUR LINES ARE DASHED WHERE SOME CONTROL IS AVAILABLE AND DOTTED WHERE THEY ARE ONLY ESTIMATIONS (from Harksen and Macdonald, 1969).

Another geologic estimate of the amount of vertical erosion that has occurred in central and western South Dakota can be made by using Harksen and Macdonald's paleotopographic map of western South Dakota (Figure 5). Hayes is situated approximately at a point where the 3200 ft paleocontour would pass if it was sketched on the map. The difference between the paleocontour and reference (2100 ft) elevations is 1,100 feet (335 m). If this value for thickness of removed material is a maximum, then the assumption is being made that very little, if any, material was deposited on top of the Ogallala. In Figure 3, the line designating the possible top of the Ogallala is based on Harksen and Macdonald's paleotopographic map.

Clearly, sufficient geological evidence, albeit somewhat circumstantial, does exist in central South Dakota to conclude that Tertiary deposits did cover that part of the state and, further, that the approximate thickness (maximum) of past overburden at the Hayes study site was 600 to 1100 feet (183 to 335 m).

While the past-overburden estimations made here, based on geologic evidence, did not involve exhaustive and detailed investigation, i.e., examination of conditions of transport, deposition, and lithification of

sediments making up the various rock units, it is believed that the estimates are accurate enough for comparison with the values determined by the other methods.

Figures 6, 7, 8, 9, 10 and 11 are photographs of sites in central South Dakota that were visited as a part of this maximum-past-overburden investigation.

Figure 6 - HAYES, SOUTH DAKOTA AREA, LOOKING WEST ALONG U.S. ROUTE 14. LOCATION "H" ON FIGURE 4.

Figure 7 - WILLOW CREEK BUTTE, STANLEY COUNTY, SOUTH DAKOTA. LOCATION "F" ON FIGURE 4.

Figure 8 - MEDICINE BUTTE, LYMAN COUNTY,
SOUTH DAKOTA.
LOCATION "K" ON FIGURE 4.

Figure 9 - GRAY-GREEN, TERTIARY QUARTZITE ON MEDICINE BUTTE, LYMAN COUNTY, SOUTH DAKOTA.
SEE FIGURE 8.

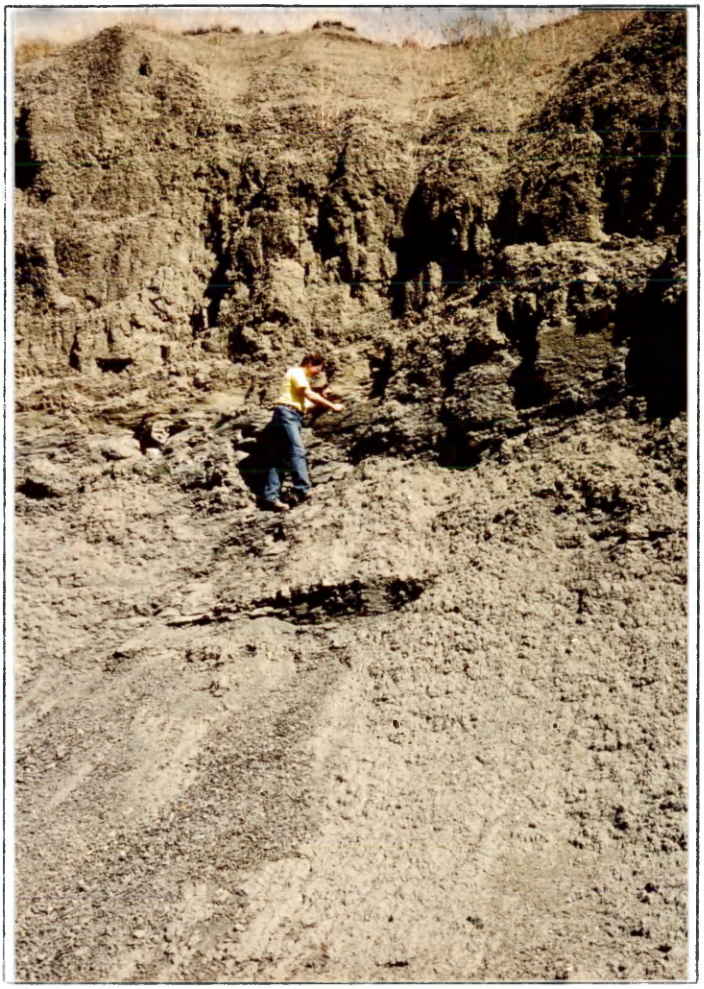


Figure 10 - PIERRE SHALE OUTCROP,
UPPER PIERRE SHALE.
NEAR LOCATION "D" ON FIGURE 4.

Figure 11 - BACULITES FOSSILS FROM OUTCROP SHOWN IN FIGURE 10.

# 3. GEOTECHNICAL DETERMINATION OF MAXIMUM PAST OVERBURDEN

## 3.1 Concepts and Definitions

In order to discuss and describe the techniques used in making the geotechnical determination of maximum past overburden, it is convenient at this point to introduce the concept of consolidation state and its relation to overburden thickness.

In simplest terms the consolidation state of a soil can be expressed as 1) normally consolidated, 2) over-consolidated, or 3) underconsolidated. A soil is said to be normally consolidated when the preconsolidation (maximum past) pressure $P_c$ just equals the existing effective vertical overburden pressure $p_o'$. A soil whose preconsolidation pressure is greater than the existing overburden pressure is said to be over-consolidated (or preconsolidated). And, a soil that has not yet come to equilibrium under the weight of the overburden load and exhibits a condition wherein the preconsolidation pressure is less than the existing effective vertical overburden pressure is termed underconsolidated. Underconsolidation can occur, for example, in soils that have only recently been deposited (usually underwater).

The comparison of the $P_c$ value with the $p_o'$ value can be done two different ways in order to determine a consolidation state for a soil. The most common way is to express the two values as a ratio of the preconsolidation stress to the existing vertical effective overburden stress. This ratio is called the overconsolidation ratio, OCR.

$$OCR = \frac{P_c}{p_o'} \text{ , and thus}$$

for OCR = 1 the soils are normally consolidated, and for OCR > 1 the soils are overconsolidated, and for OCR < 1 the soils are underconsolidated.

A second way to relate the two values, $P_c$ and $p_o'$, is by subtracting the vertical effective overburden stress from the preconsolidation stress and presenting the new stress value as the overconsolidation difference, OCD. OCD is useful in describing the consolidation state of recent marine sediments where the use of the OCR can be misleading (Olsen, Rice, Mayne, and Singh, 1986).

$$OCD = P_c - p_o', \text{ and thus}$$

for OCD = 0 the soils are normally consolidated, and for OCD > 0 the soils are overconsolidated, and for OCD < 0 the soils are underconsolidated.

OCR and OCD values for cores from the Hayes study site are presented and discussed later in this report. These values indicate the Pierre Shale at the study site is overconsolidated. This finding was expected since clay shales in general usually exhibit high degrees of overconsolidation, and, more specifically, the Pierre Shale has been described as overconsolidated by past investigators (Fleming and others, 1970).

When soil (clay) layers covering a large area are loaded vertically, whether by the weight of overlying sediments or some other mechanism, the compression can be assumed to be one dimensional. To simulate one-dimensional compression in the laboratory, the soil is compressed in a special device called a consolidometer. The details for conducting such a test will not be given here; however, the test procedures should generally conform to the recommendations of ASTM D 2435-80 or D 4186-82.

The object of the consolidation test is to simulate the compression of the (in situ) soil under given external loads. What is being measured is in fact the modulus of the soil in confined compression. By evaluating the compression characteristics of an "undisturbed" representative sample, the change in thickness of the (in situ) soil due to the loading can be predicted.

Engineers use several methods to present load-deformation data. The most common way to present the data is by plotting the void ratio (e) versus the logarithm of effective consolidation stress (log p).

For an "undisturbed" clay sample, the void ratio versus log pressure plot will normally have two approximately straight-line portions connected by a smooth transitional curve. The stress at which the transition or "break" occurs in the curve is an indication of the maximum vertical overburden stress that the sample has sustained in the past; this stress is known as the preconsolidation pressure $P_c$. The initial flatter portion of the e-log p consolidation curve is termed the reconsolidation curve, and the part after the break in the curve is called the virgin compression curve. (Figure 12). As the name "virgin" implies, the soil has never before experienced a stress greater than the preconsolidation stress.

## 3.2 Method of Estimating Preconsolidation Pressure

The preconsolidation pressure can be estimated by a number of methods, including those of Burmister (1951), Janbu (1969), and Schmertmann (1955). The method which is most widely used in practice and which is generally

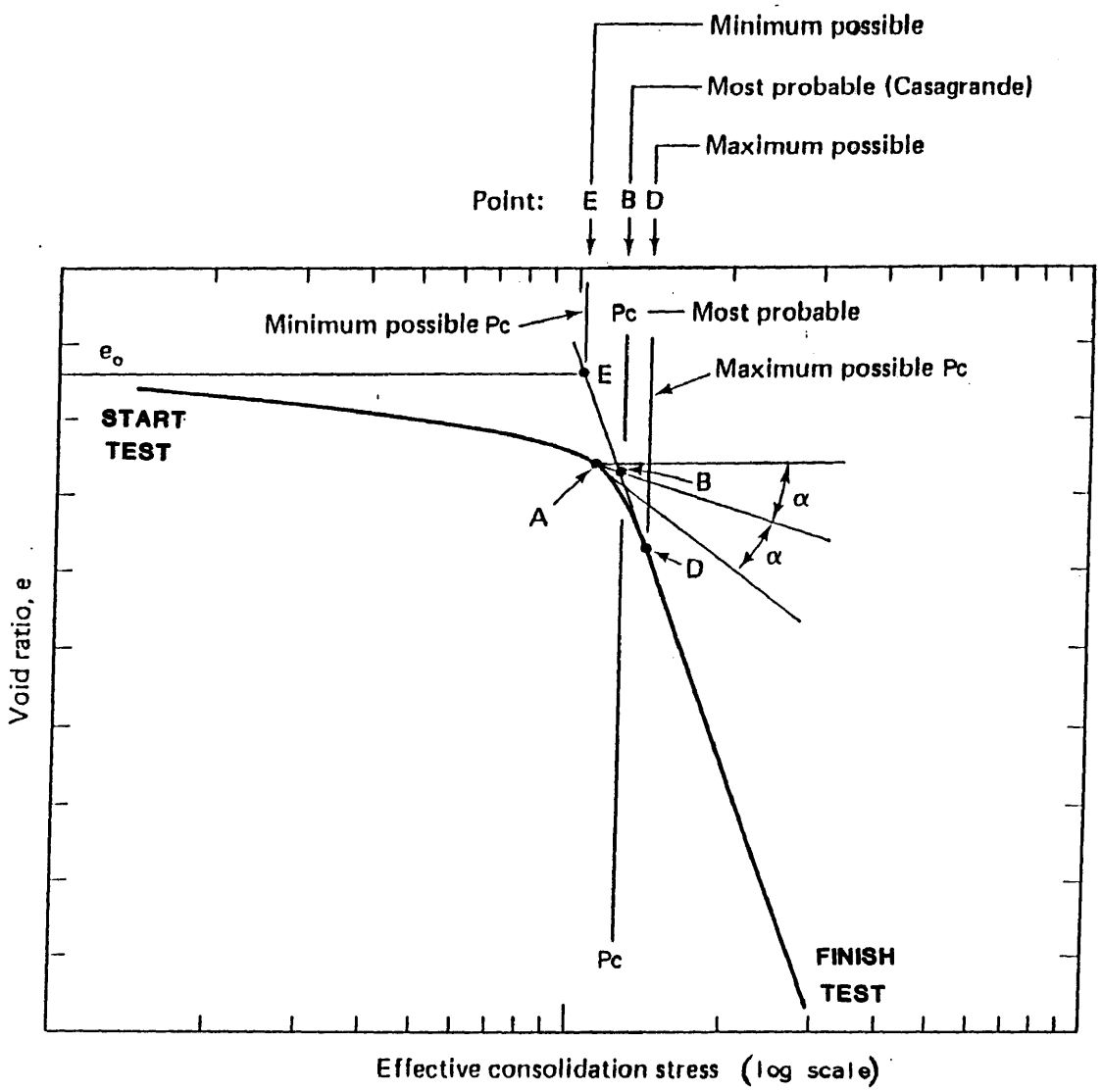



Figure 12 - THE CASAGRANDE (1936) CONSTRUCTION FOR DETERMINING THE PRECONSOLIDATION STRESS. ALSO SHOWN ARE THE MINIMUM POSSIBLE, THE MOST PROBABLE, AND THE MAXIMUM POSSIBLE PRECONSOLIDATION STRESSES (modified from Holtz and Kovacs, 1981).

considered to yield satisfactory results if samples are of high quality and consolidation tests are properly conducted is the Casagrande method (Brumund and others, 1976). For a critical review of the Casagrande method for estimating $P_c$ the reader is referred to Dean (1984).

Arthur Casagrande (1936) presented the empirical method shown in Figure 12 and outlined below for estimation of the value of $P_c$ from the results of laboratory consolidation tests on undisturbed samples of saturated clay. The procedure is applicable to both void ratio versus log pressure curves and vertical strain (or change in sample height) versus log pressure curves.

The Casagrande procedure is as follows:

1. Choose by eye the point of minimum radius (or maximum curvature) on the consolidation curve (point A in Figure 12).
2. Draw a horizontal line from point A.
3. Draw a line tangent to the curve at point A.
4. Bisect the angle made by steps 2 and 3.
5. Extend the straight line portion of the virgin compression curve up to where it meets the bisector line obtained in step 4. The point of intersection of these two lines is the preconsolidation stress (point B of Figure 12).

Figure 12 also shows how a range of $P_c$ values can be determined for a single consolidation test sample. The minimum possible $P_c$ to the maximum possible $P_c$ defines the range.

The comments from Dean (1984) and other investigators who have used the Casagrande method and critically evaluated it tend to incorporate at least one of the following three ideas in their comments:

1. Instead of reporting a single definitive preconsolidation stress value, a range of values should be defined. (The technique for doing this was demonstrated in Figure 12.)
2. In many instances, particularly for soils known to be highly overconsolidated, the Casagrande method for determining $P_c$ underestimates the preconsolidation stress (Khera and Schulz, 1984, among others).
3. As long as its limitations are generally understood, the Casagrande construction should and will continue to be used because of the simplicity of it.

In order to understand why it is possible to predict the preconsolidation pressure using graphical procedures such as the Casagrande construction, it is necessary to

examine the complete stress-strain history of a sedimentary clay soil during deposition, sampling, and reloading in the laboratory by the consolidometer. The stress history of a clay soil during deposition (and erosion) can be understood by looking at Scott and Brooker's (1966) illustration of effective overburden stress versus time for the Bearpaw Shale of western Canada (Figure 13). The Bearpaw Shale is an upper Cretaceous stratigraphic equivalent of the Pierre Shale of this report. The stress-strain history of a clay soil during sampling and reloading in the laboratory is illustrated in Figure 14. A comparison of Figures 12 and 14 shows why $P_c$ values determined by the Casagrande construction will vary quite substantially for similar soil specimens when one sample is relatively "undisturbed" and the other is disturbed.

## 3.3 High-Pressure Consolidation Testing Procedures and Equipment

Two different high-pressure consolidometers were used to obtain the consolidation data analyzed for this study. One belonged to the Army Corps of Engineers and the other was a USGS apparatus. This author used the USGS consolidometer to conduct six consolidation tests on Pierre Shale

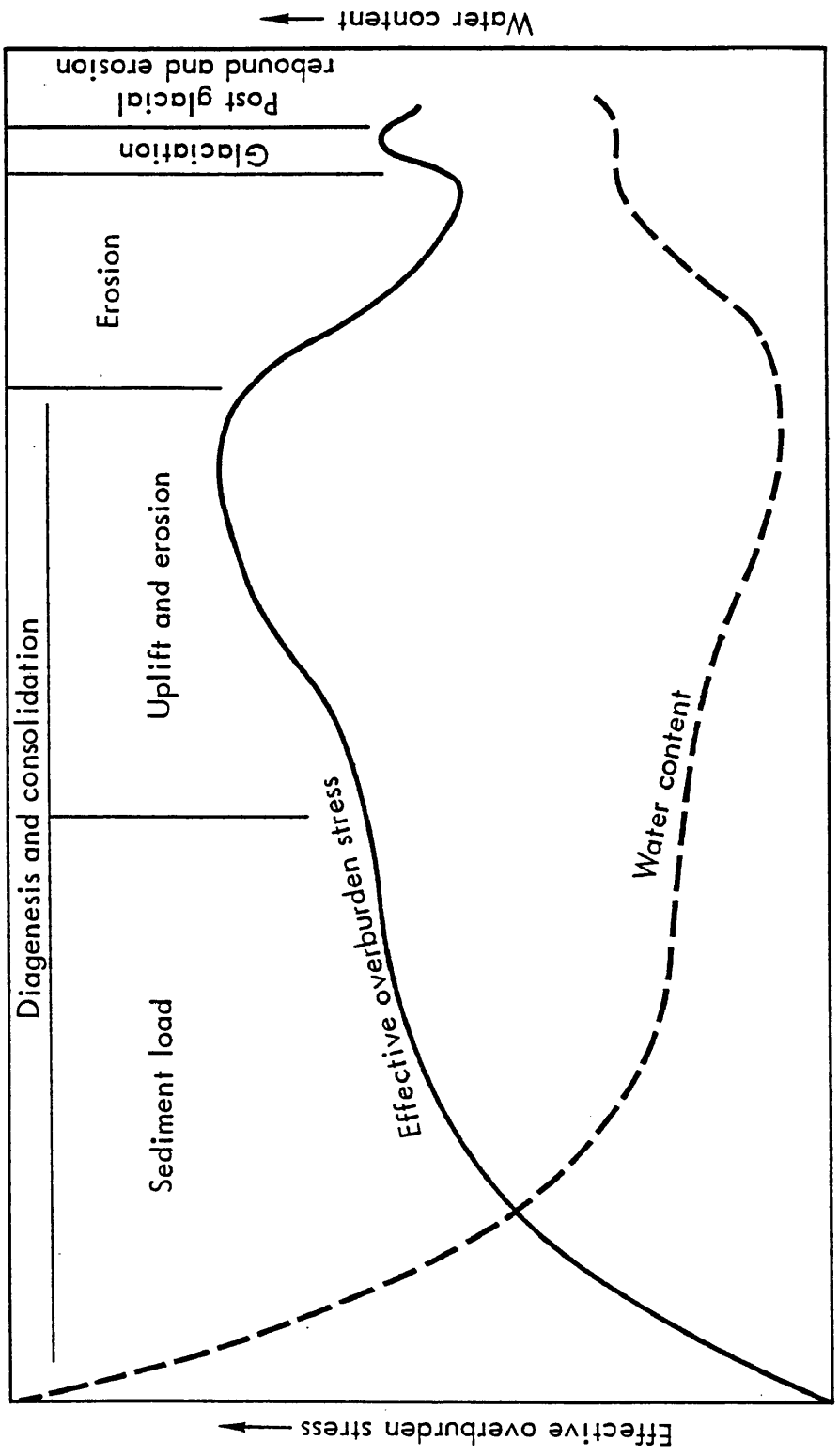



Figure 13 - PROBABLE STRESS HISTORY OF BEARPAW SEDIMENTS (from Scott and Brooker, 1968).

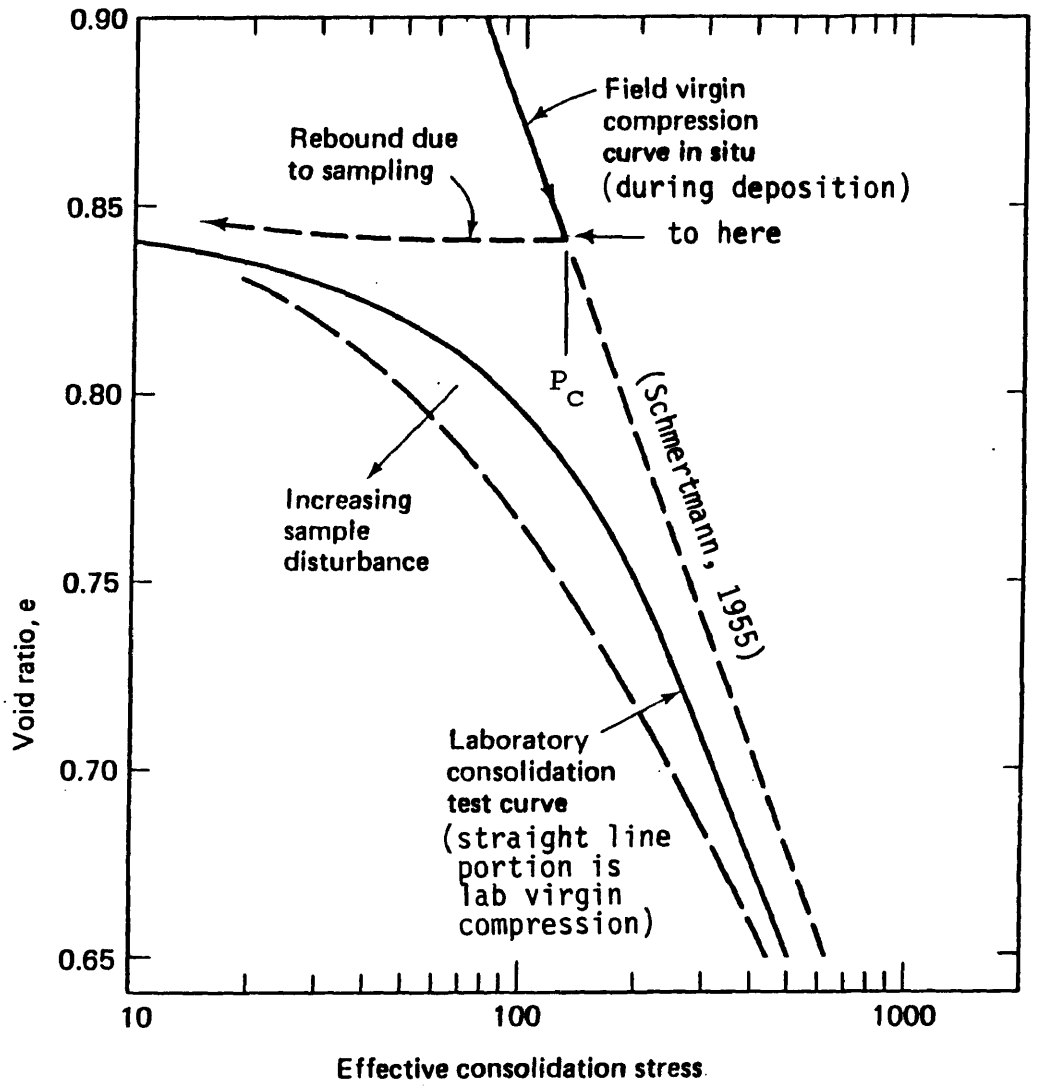



Figure 14 - VOID RATIO VERSUS LOG PRESSURE CURVE ILLUSTRATING DEPOSITION, SAMPLING (UNLOADING) AND LABORATORY RECONSOLIDATION IN THE CONSOLIDATION TEST APPARATUS (modified from Holtz and Kovacs, 1981).

samples from Hayes, South Dakota. Eight consolidation tests on Pierre Shale samples from Hayes were run on the Corps of Engineers apparatus by their technicians. No details were available from the Corps of Engineers concerning sample preparation techniques and mechanical aspects of the consolidometer. Therefore, the consolidation data obtained from the Corps' tests had to be taken at face value.

The high-pressure consolidometer used in conducting the six USGS consolidation tests for this study is shown in Figures 15 and 16. In addition to being designed and built so that pore fluid from the clay-shale specimens could be collected for chemical analyses, the USGS apparatus and associated systems can also be used for flow-pump permeability testing and chemical-osmosis testing.

The basic apparatus is a redeveloped piece of equipment used by H. W. Olsen in the late 1960's during his investigations of liquid movement through kaolinite under hydraulic, electric, and osmotic gradients (Olsen, 1972).

Figure 15 is a schematic diagram of the principal component of the USGS high-pressure consolidometer. The pressure source for the pistons is a custom-built

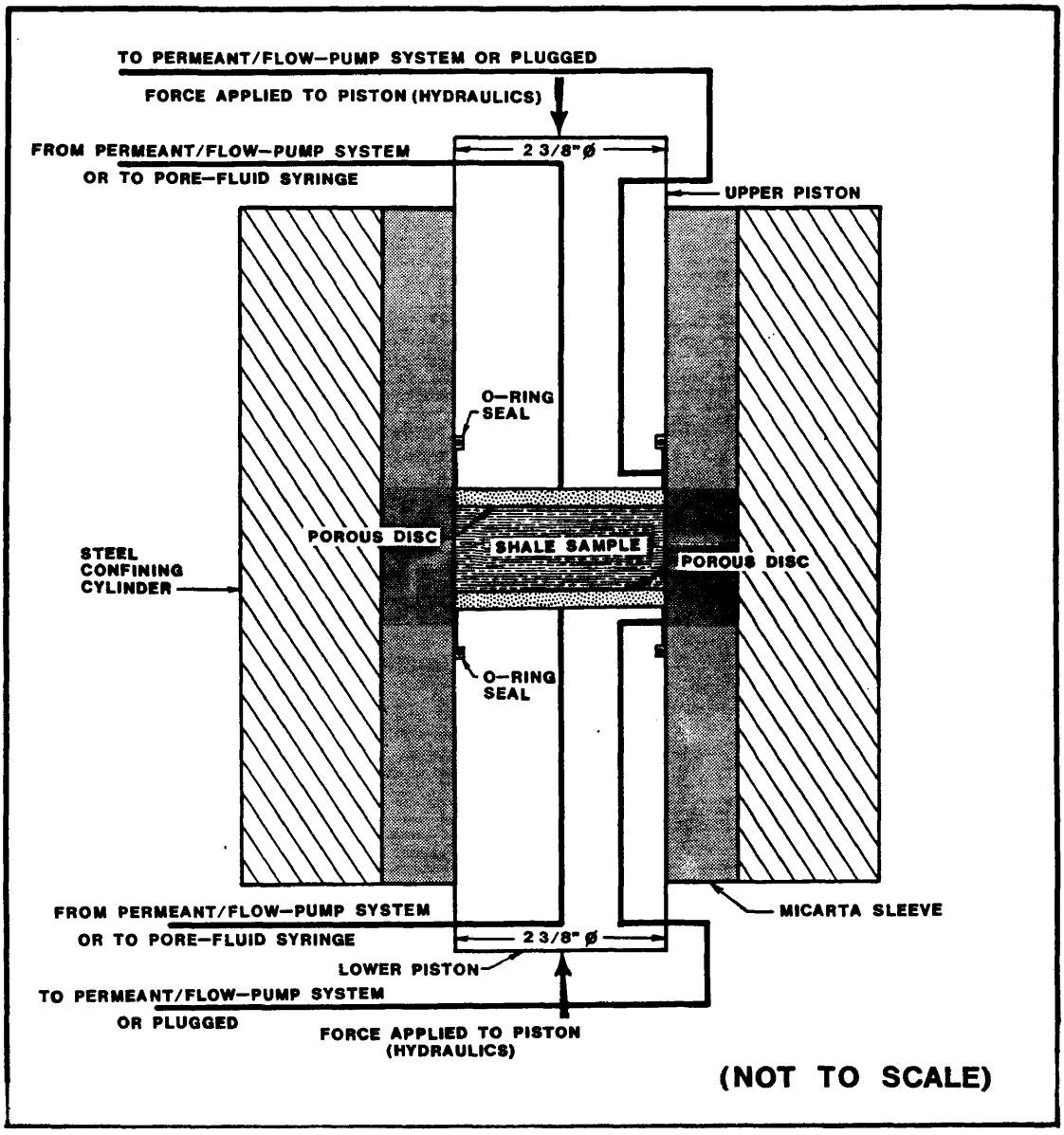



Figure 15 - SCHEMATIC DIAGRAM OF USGS HIGH-PRESSURE CONSOLIDOMETER.

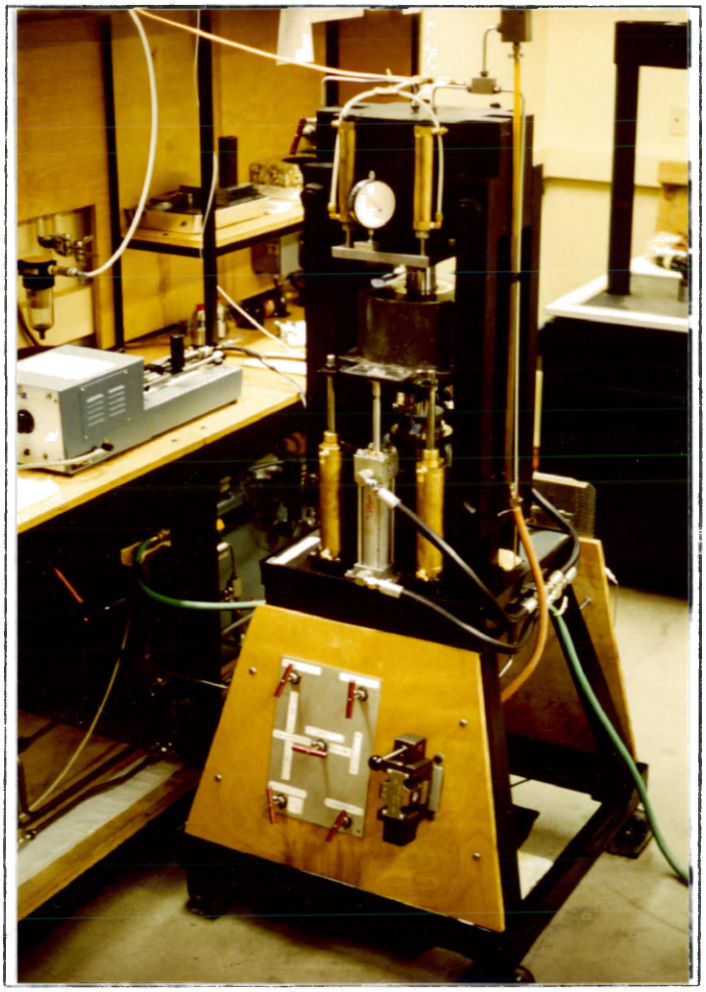


Figure 16 - USGS HIGH-PRESSURE CONSOLIDOMETER.

hydraulic pumping unit which will deliver anywhere between 400 and 2000 pounds per square inch ($lbs/in^2$) of line pressure. The line pressure can be reduced in half to as low as 200 $lbs/in^2$ by going through a pressure-reducing valve on the apparatus, or it can be boosted to as high as 30,000 $lbs/in^2$ by going through a 15-to-1 pressure intensifier. The line pressure is applied to the outer end-surfaces of 4-inch-diameter loading pistons which in turn load the 2 and 3/8-inch-diameter pistons shown in the schematic. The 2 and 3/8-inch value for the piston diameter was selected after a trimming technique for the shale samples was developed. This techinque, described later, allows cored-shale specimens to be trimmed to a uniform diameter of 2 and 3/8-inches. The diameters of the sample-contact pistons and the shale specimen must match.

Although both the upper and lower pistons can be loaded at the same time, during a consolidation test only one piston (usually the upper) is hydraulically loaded and the other remains stationary. The reduction in piston size from 4 inches to 2 and 3/8 inches creates an applied pressure on the sample which is 2.84 times the line pressure on the 4-inch-diameter loading pistons. Thus, the maximum pressure that can be delivered to a sample in this consolidometer is 85,200 $lbs/in^2$, or 6134 tons per

square foot (tons/ft$^2$). The consolidation tests indicated that pressures beyond 1000 tons/ft$^2$ were not necessary for consolidating the Pierre Shale samples; in other words, virgin compression, as indicated by the e-log p curves, was achieved long before reaching 1000 tons/ft$^2$.

As indicated in Figure 15 the 2 and 3/8-inch-diameter loading pistons (stainless steel) operate inside of a micarta (epoxy-bonded glass fibers) sleeve. This arrangement was necessary for two reasons: 1) when both the sleeve and pistons are made out of stainless steel, and if alignment of the pistons and sleeve is not absolutely perfect, a very damaging and expensive "lock-up" will occur, and 2) a confining sleeve made out of non-conductive material is needed for the osmotic-gradient tests for which this apparatus will be used in the future.

The shale specimens that were used for consolidation testing in the USGS consolidometer came from cores that were obtained during a 1982 drilling program conducted near Hayes, South Dakota. The cores represented 5-ft sections taken at 50-ft intervals down through 595 feet of the Pierre Shale sequence. The cores were transported to Denver, Colorado where, after being x-rayed, they were placed in cold storage in semi-upright position still

sealed inside the 5-ft lengths of steel drill tube. The intervals for subsampling for consolidation-test specimens were selected after examination of the radiographs. Because of the age of the cores (2 years old at the time of the tests), the time available for testing to be completed, and the length of time required for each test, it was decided that six specimens from six evenly-spaced depths would be sufficient for the test program. Thus, when the subsampling and testing were completed, laboratory consolidation information was available from depths of 96 ft, 159 ft, 232 ft, 412 ft, 502 ft, and 564 ft for the core from site H12 at Hayes.

Consolidation testing started in mid-1984 and was completed by the end of the same year. Six other specimens from H12 had been used for pore fluid extraction in the high-pressure consolidometer prior to the start of consolidation testing.

Each of the six samples selected for consolidation testing was subjected to the same type of preparation for the test. Because of variation in diameter of the core from the nominal 2 and 7/16-inch-value, and other core-surface aberrations related to drilling and storage, a decision was made to trim all consolidation test specimens approximately 1/16 inch to a diameter of 2 and

3/8 inches. A six-inch-long piece of intact shale was chosen from the 5-ft section of core. The sample was then split into two 3-inch-long pieces. One piece was wrapped in foil and saved and the other one was placed in a trimming device designed especially for use on these shale samples.

The trimming device, shown in Figure 17, was a modified soil-lathe which was adapted for use on a drill press. The cutting bit remained stationary while the sample rotated and a 1 and 1/2-inch-long section of the specimen was trimmed to a diameter of 2 and 3/8 inches. A split-ring collar was clamped around this exposed 2 and 3/8-inch-diameter section. This "secured" 1 and 1/2-inch-long piece was cut away from the rest of the sample and the ends were trimmed (ground) until a right-circular cylinder was formed. A water spray mist was used on the sample during this trimming procedure to keep the shale from drying out.

The difficulty in trimming the ends of the samples varied and as a result the heights of the six test specimens also varied. The trimmed heights ranged from approximately one to one-and-a-half inches. A diameter-to-height ratio of at least 2.5 is recommended for one-dimensional consolidation testing (Brumund and others, 1976).

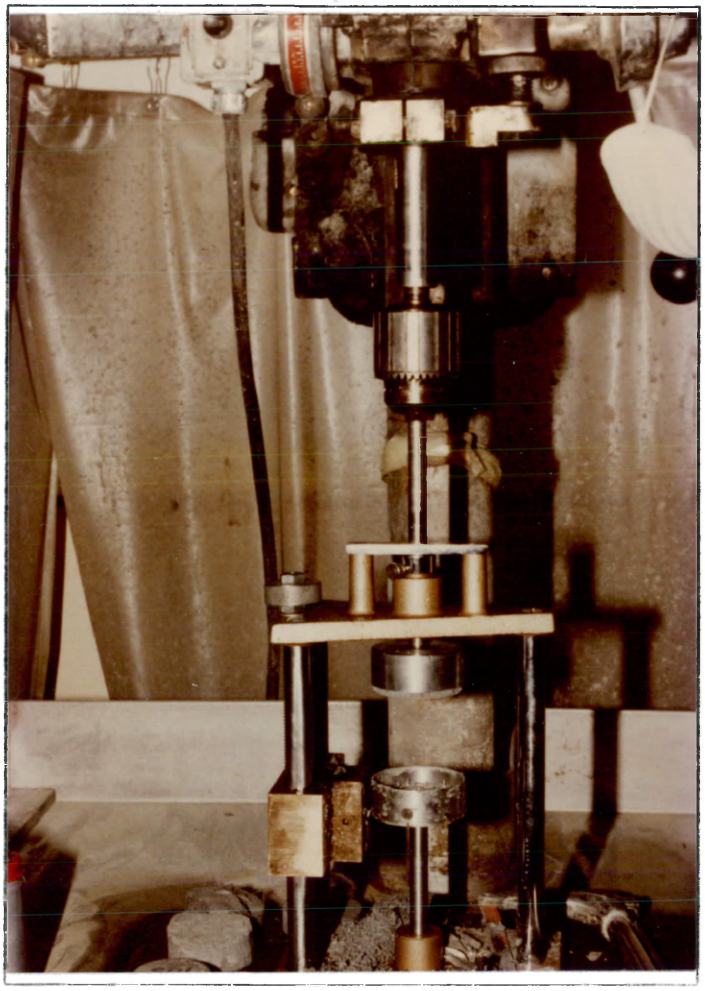


Figure 17 - TRIMMING DEVICE FOR CORED SHALE SPECIMENS.

## 3.4 Corps of Engineers Test Data and Maximum-Past-Overburden Values

Eight Pierre Shale samples from site H2 cores were tested by the Corps of Engineers at their division laboratory in Omaha, Nebraska. The results of these high-pressure consolidometer tests are presented in Figures 18 through 25 as void ratio (e) versus log pressure (log p) curves. In each of the eight tests the maximum vertical pressure that was applied was 350 tons per square foot (342 $kg/cm^2$).

In addition to the loading (recompression) part of the consolidation curve (generally concave down on e-log p plots) each of the eight plots also shows a swelling (rebound) segment. This rebound phase of the test (where the curve indicates a swelling of the sample to a void ratio higher than the initial void ratio $e_o$) is shown simply because it was a part of the overall consolidation test conducted by the Corps of Engineers. For all practical purposes, this final rebound phase is not needed for determining preconsolidation pressures when using the Casagrande construction. The significance of this rebound curve and what it indicates as related to preconsolidation will not be discussed here.

CORPS OF ENGINEERS TESTS

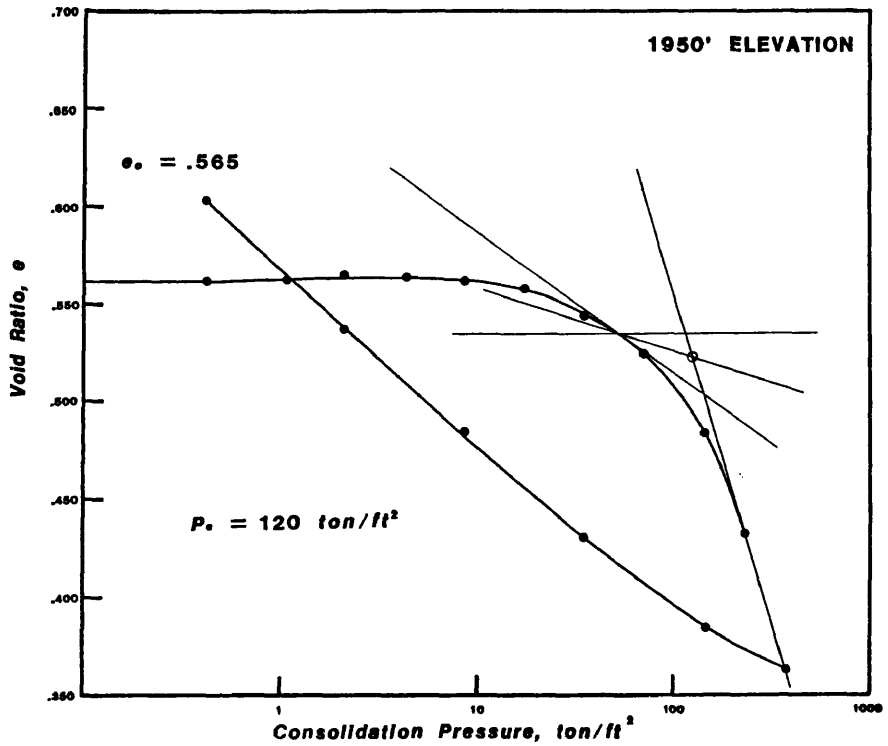



Figure 18 - LAB CONSOLIDATION CURVE, H2 78'.

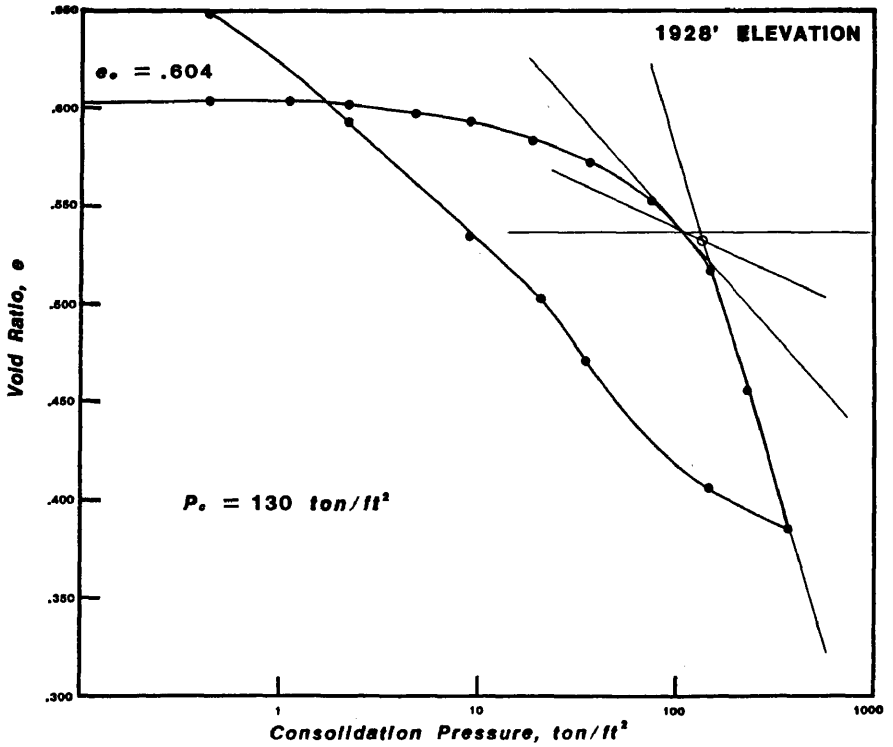



Figure 19 - LAB CONSOLIDATION CURVE, H2 102'.

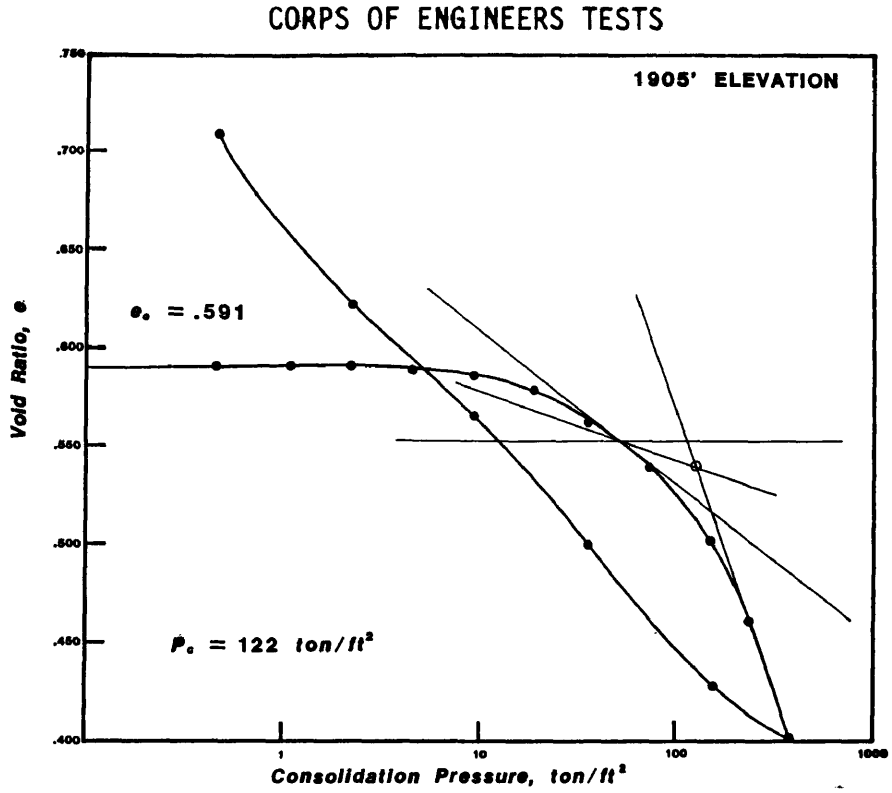



Figure 20 - LAB CONSOLIDATION CURVE, H2 125'.

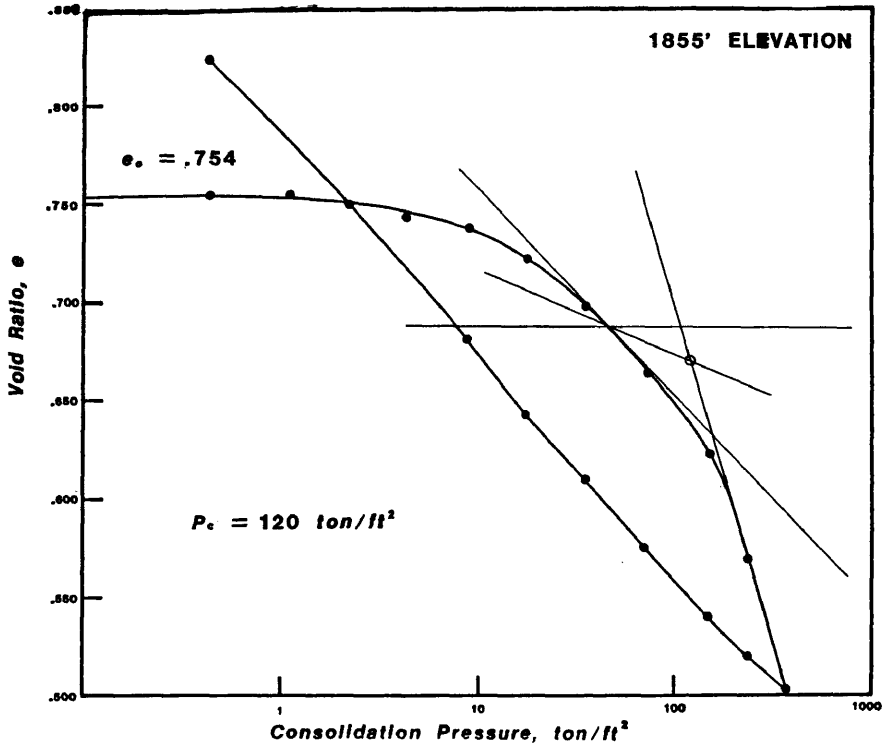



Figure 21 - LAB CONSOLIDATION CURVE, H2 175'.

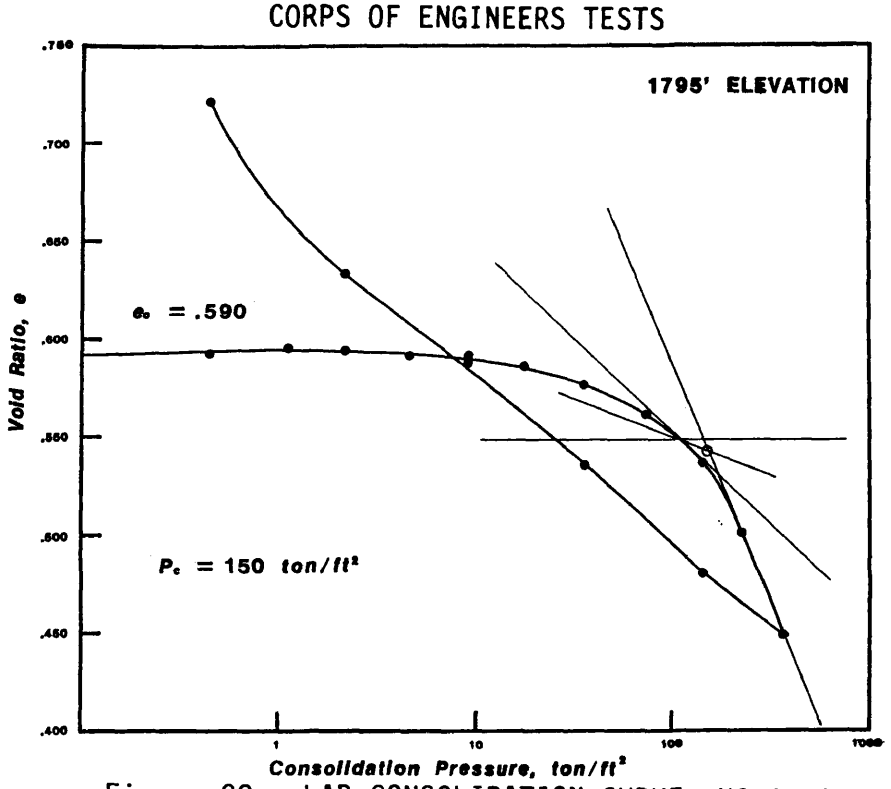



Figure 22 - LAB CONSOLIDATION CURVE, H2 235'.

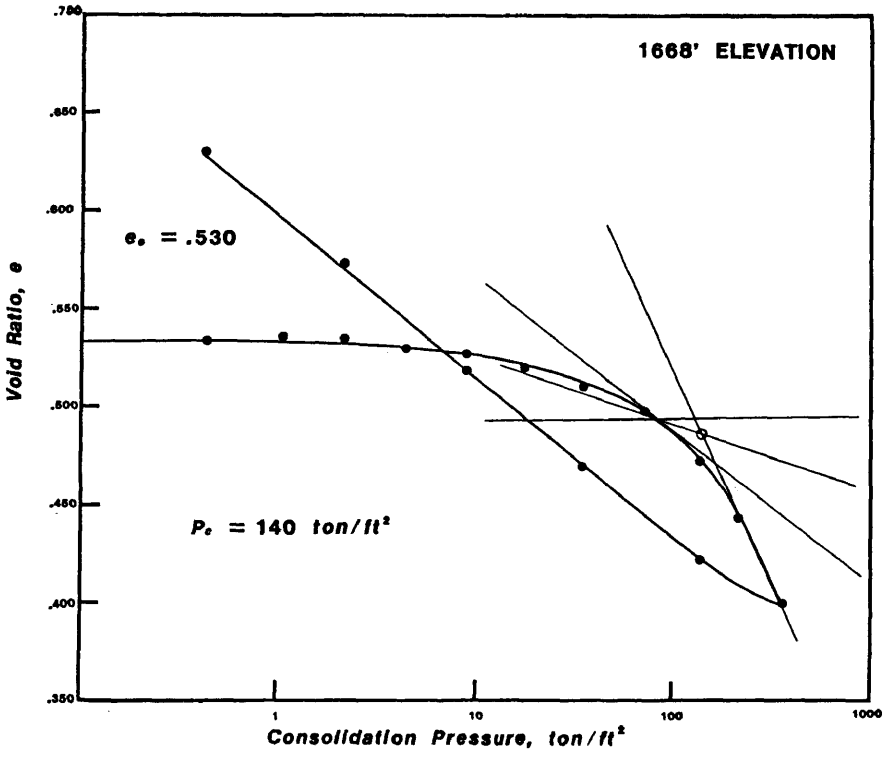



Figure 23 - LAB CONSOLIDATION CURVE, H2 362'.

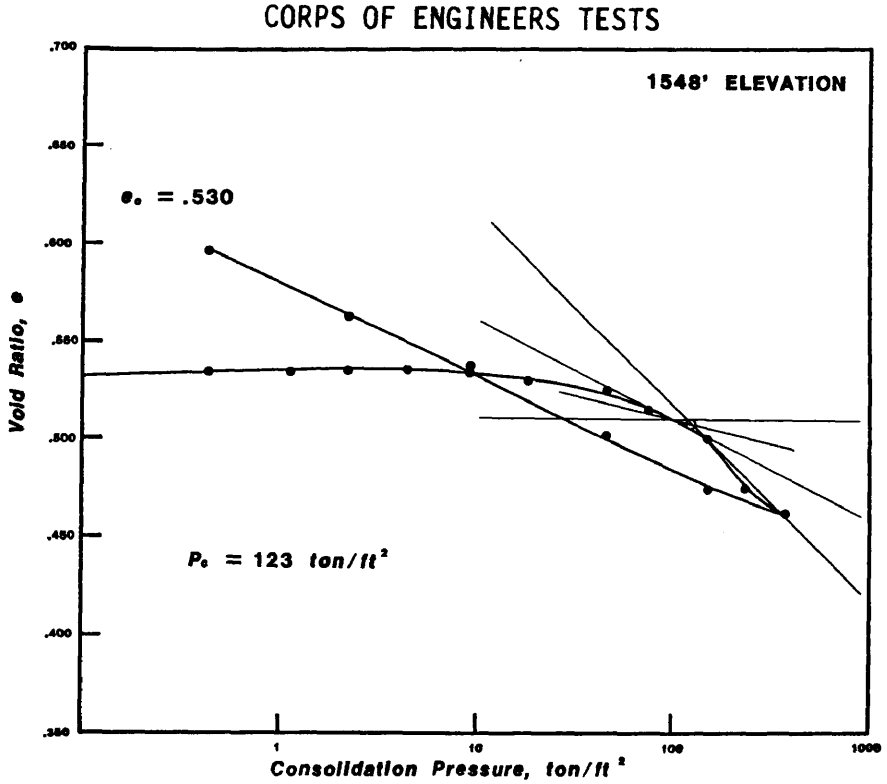



Figure 24 - LAB CONSOLIDATION CURVE, H2 482'.

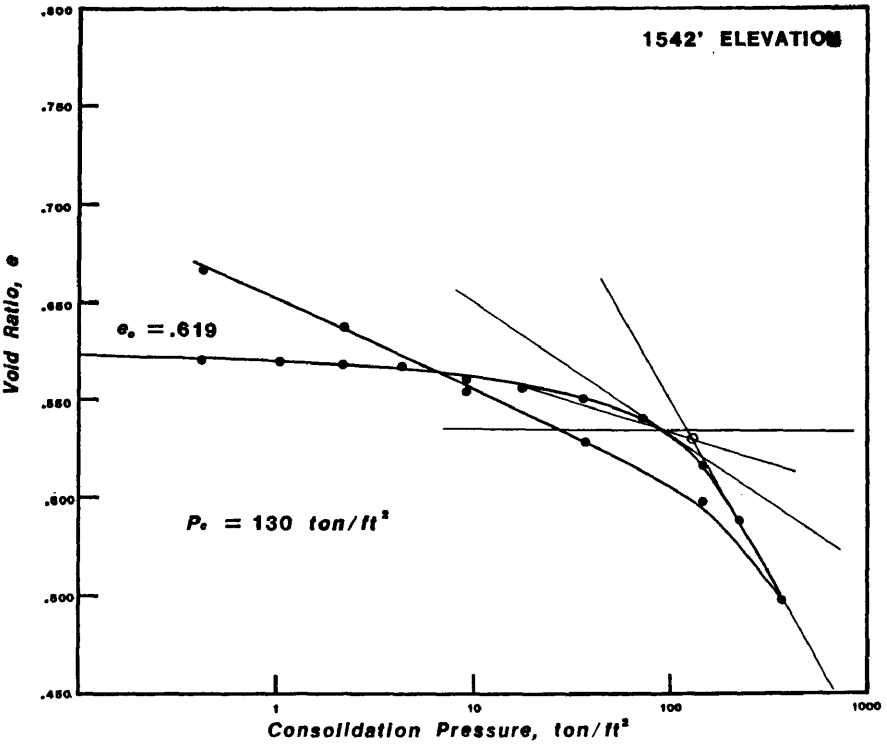



Figure 25 - LAB CONSOLIDATION CURVE, H2 488'.

The Casagrande construction (Casagrande, 1936) used in determining the preconsolidation pressure of each sample is also shown in Figures 18 through 25. Once the preconsolidation pressures were determined, the overconsolidation ratios (OCR) and the overconsolidation differences (OCD) were calculated. The present day (estimated in situ) vertical effective stress $p_o'$ values for the H2 samples were determined by taking the saturated unit weight and subtracting the unit weight of salt water (64 lbs/ft$^3$ or 1.025 g/cm$^3$) to get the submerged unit weight. The submerged unit weight was then multiplied by the amount of existing overburden to determine the vertical effective stress. These stress values are reasonably accurate if it is assumed the Pierre Shale sequence is saturated from the surface down. This assumption is basically valid as indicated by the saturation measurements that were done on samples from both H2 and H12 cores (unpublished data from Corps of Engineers and U.S. Geological Survey).

Table 2 lists $P_c$, $p_o'$, OCR, OCD, and calculated amount of past overburden for each tested sample from site H2 at Hayes, South Dakota. Under the column listing the $P_c$ values there are three numbers shown (separated by hyphens) for each sample. The first and last numbers represent minimum and maximum $P_c$ values. These two

TABLE 2 - Geotechnically Derived Values of $P_c$, $p_o'$, OCR, OCD, and Calculated Amounts of Past Overburden for Pierre Shale Samples from H2

| SAMPLE DEPTH (ft) | SAMPLE ELEVATION (ft) (Above sea level) | $P_c$(tsf) min.-$P_c$-max. | $p_o'$(tsf) | OCR | OCD (tsf) | AMOUNT OF PAST OVERBURDEN (ft)[1] (using 2100' elevation datum plane) |
|---|---|---|---|---|---|---|
| 80 | 1950 | 95-120-220 | 2.6 | 46 | 117 | 3540 |
| 102 | 1928 | 80-130-160 | 3.5 | 37 | 126 | 3770 |
| 125 | 1905 | 84-122-230 | 4.2 | 29 | 118 | 3395 |
| 175 | 1855 | 70-120-185 | 5.0 | 24 | 115 | 3825 |
| 235 | 1795 | 97-150-187 | 7.9 | 19 | 142 | 4175 |
| 362 | 1668 | 87-140-215 | 12.9 | 11 | 127 | 3460 |
| 482 | 1548 | 70-123-158 | 17.1 | >7 | 106 | 2965 |
| 488 | 1542 | 78-130-218 | 14.9 | <9 | 115 | 3640 |
| | | | | | average: 121 tsf | average: 3595 ft. |
| | | | | | | use: 3600 ft. |

Surface elevation = 2030 ft.

$P_c$ = preconsolidation pressure (based on interpretation of Corps of Engineers tests)

$p_o'$ = (estimated) in situ vertical effective stress

OCR = overconsolidation ratio, $P_c/p_o'$

OCD = overconsolidation difference, $P_c - p_o'$

[1] Past overburden calculations based on assumption that entire sequence of sediments was continually acted upon by buoyant forces.

values and the $P_c$ range that they define were not used in calculating any amounts of past overburden; only the middle value in the $P_c$ column was used. The values in the last column of the table indicate the amount of overburden that has been eroded away from above a 2100 ft elevation datum plane (reference elevation).

The rounded average for the geotechnically derived amount of past overburden (above 2100 ft elevation) at site H2 is 3600 feet (1100 m). This amount of past overburden was calculated based on the assumption that the entire sequence of sediments was continually acted upon by buoyant forces. Buoyancy and its role in the discrepancy issue are discussed in Chapter 4.

## 3.5 U.S. Geological Survey Test Data and Maximum-Past-Overburden Values

Six Pierre Shale samples from site H12 cores were tested by this author using a high-pressure consolidometer located at the USGS geotechnical laboratory in Denver, Colorado. The results of these tests are presented in Figures 26 through 31 as void ratio (e) versus log pressure (log p) curves. In five of the six tests the maximum vertical pressure that was applied was 350 tons per square foot (342 $kg/cm^2$). One test (Figure 30) had

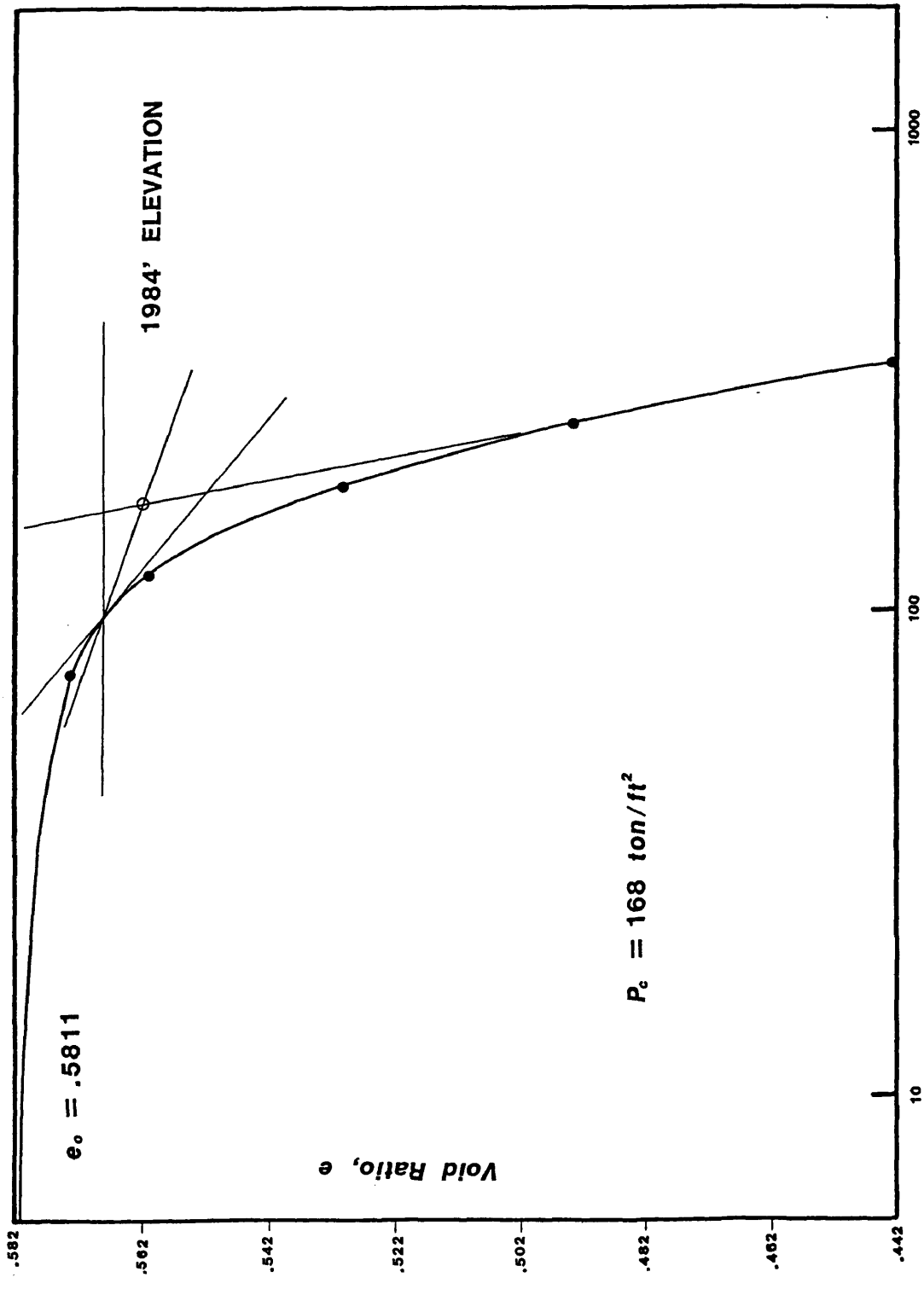



Figure 26 - LABORATORY CONSOLIDATION CURVE, H12 96'.

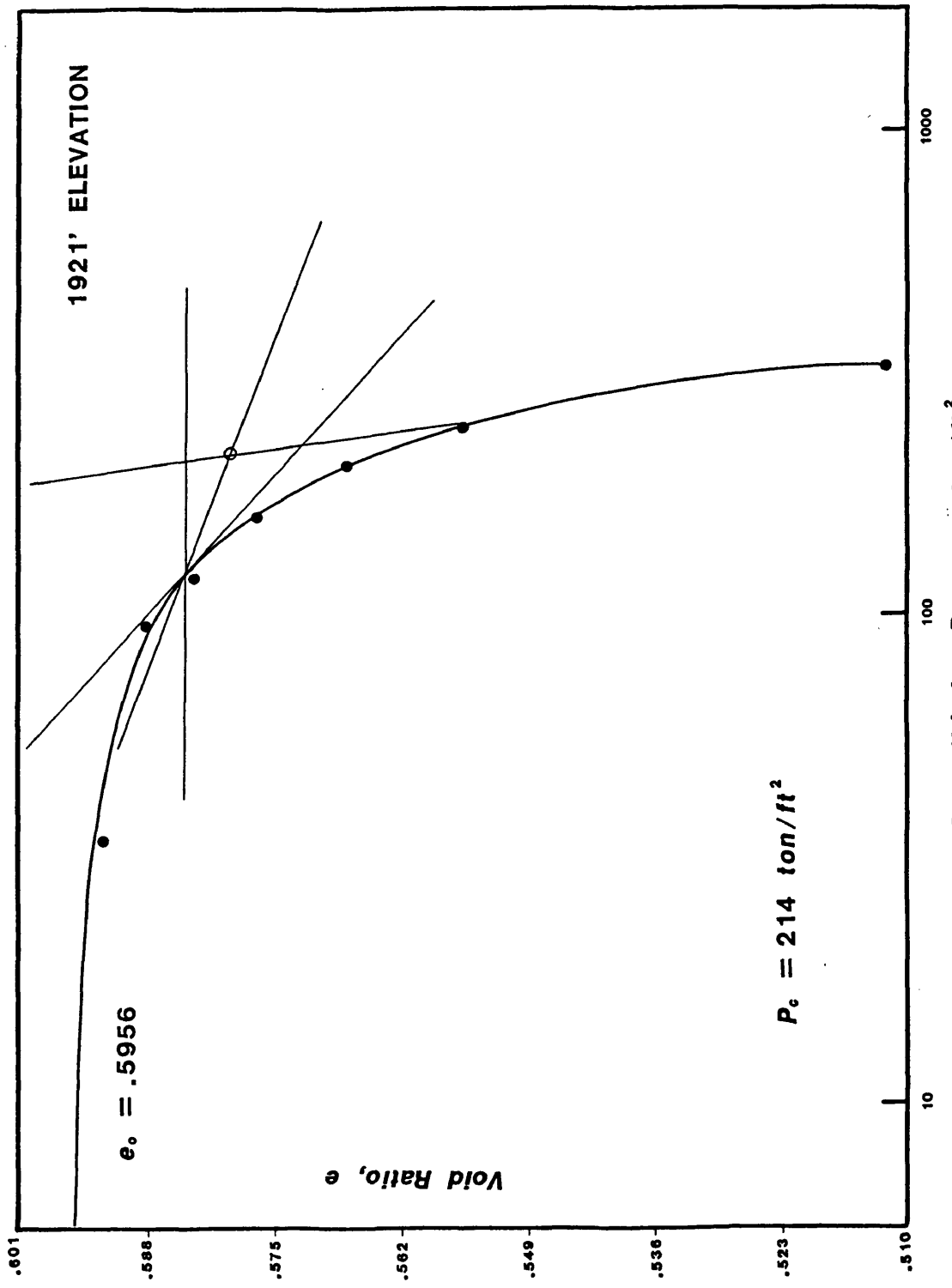



Figure 27 - LABORATORY CONSOLIDATION CURVE, H12 159'.

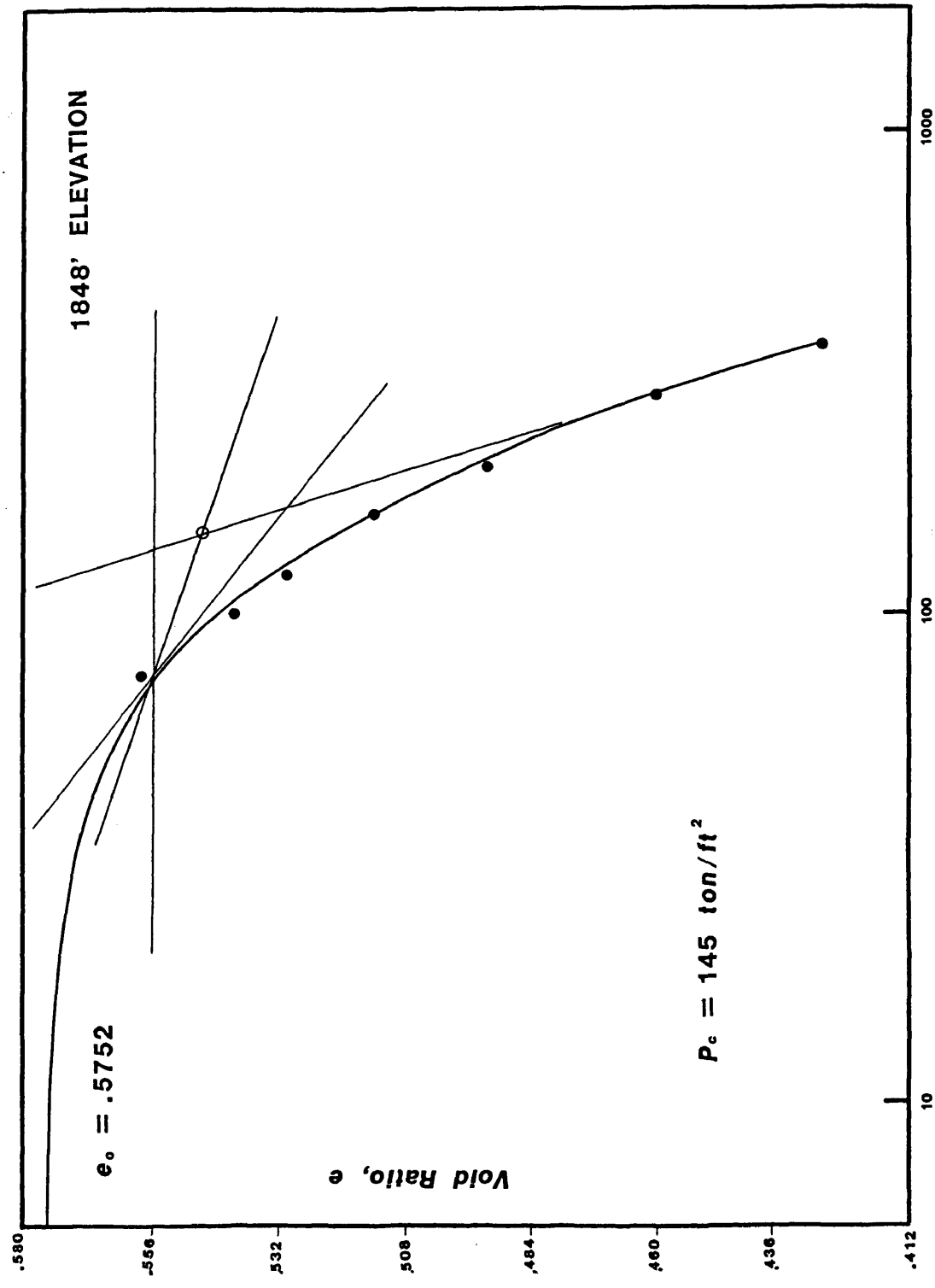



Figure 28 - LABORATORY CONSOLIDATION CURVE, H12 232'.

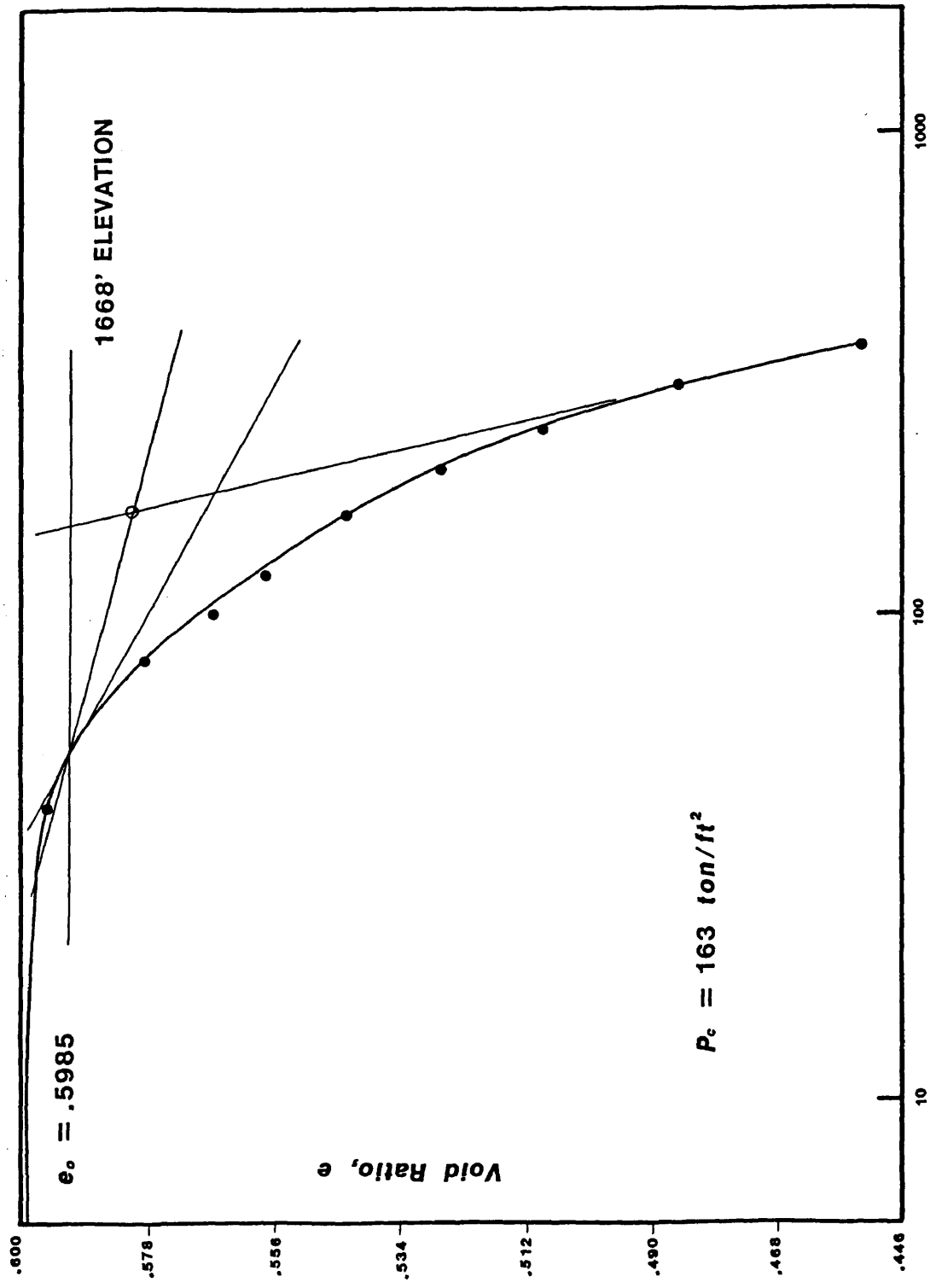



Figure 29 - LABORATORY CONSOLIDATION CURVE, H12 412'.

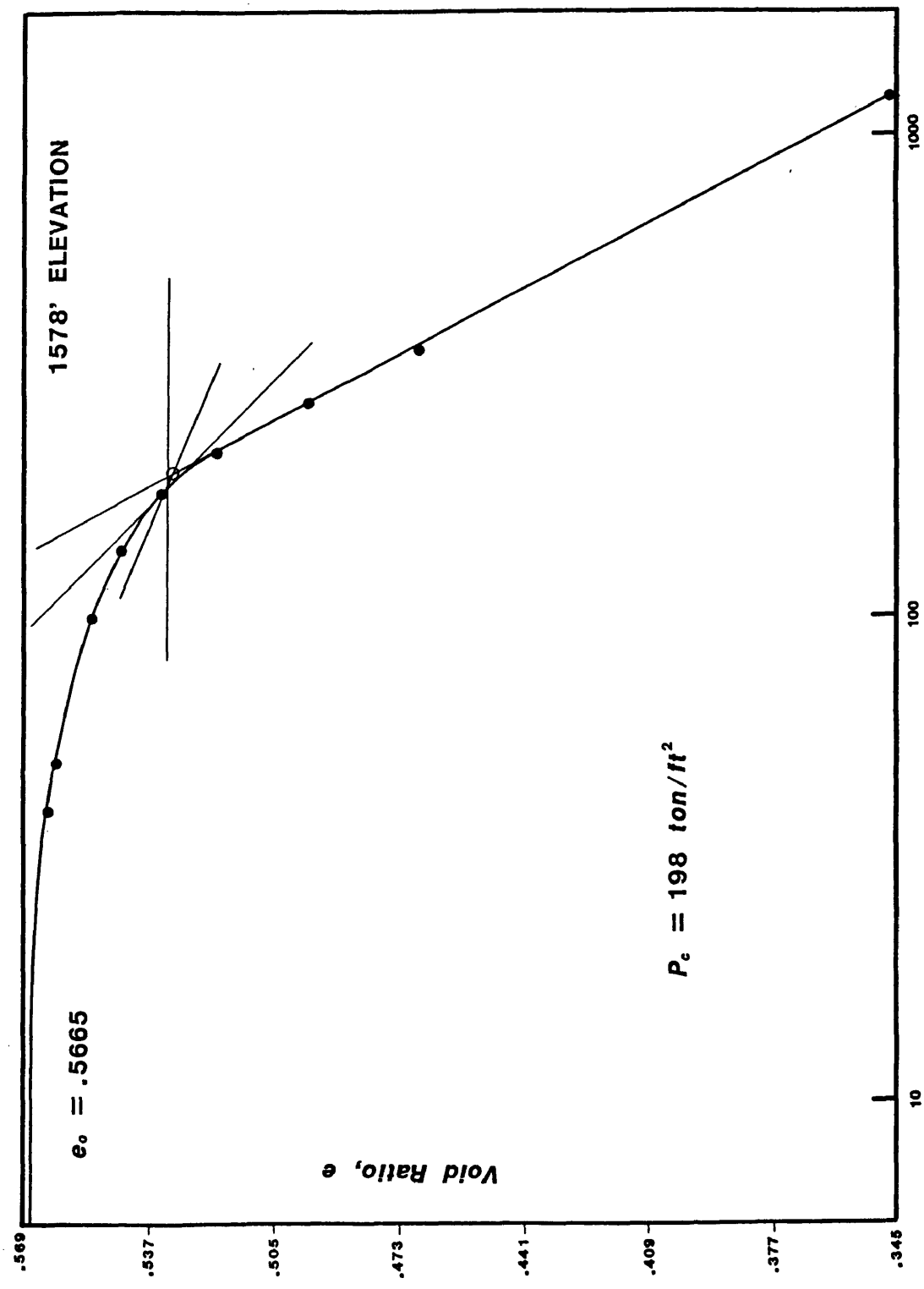



Figure 30 - LABORATORY CONSOLIDATION CURVE, H12 502'.

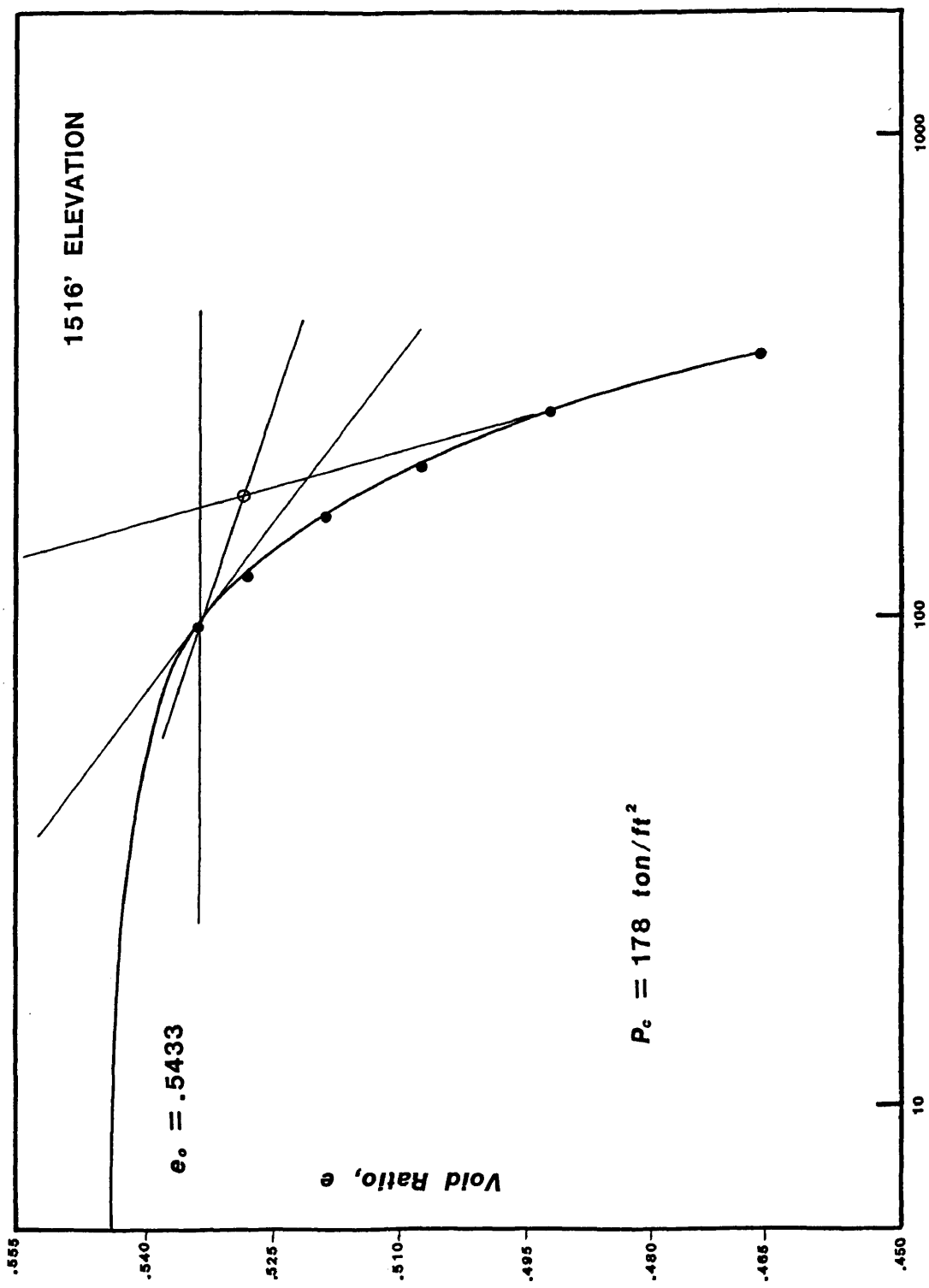



Figure 31 - LABORATORY CONSOLIDATION CURVE, H12 564'.

a final applied pressure of 1160 tons/ft$^2$ (1133 kg/cm$^2$).

After determining $P_c$ and $p_o'$ for each of the USGS samples, the OCR, OCD, and amount of past overburden were calculated. These values are listed in Table 3. The discussion presented in the previous section to explain Table 2 also applies to Table 3.

The rounded average for the geotechnically derived amount of past overburden (above 2100 ft elevation) at site H12 is 5000 feet (1525 m).

## 3.6 Additional Interpretation of Corps of Engineers and USGS Data

In this section, three figures are presented which allow for a comparison between the Corps of Engineers and U.S. Geological Survey test data. Figures 32 and 33 show test data from this study, while Figure 34 is a conceptual diagram.

Figure 32 shows the plot of overconsolidation ratio (OCR) versus depth for both the Corps of Engineers and USGS tests. A visual best-fit curve was drawn through all of the points. By picking OCR values from this curve and back-calculating, the estimated value of past overburden for site H2 was 3780 ft (1152 m) and for H12 was 4740 ft (1445 m). As with the calculations done in Sections 3.4

TABLE 3 - Geotechnically Derived Values of $P_c$, $p_o'$, OCR, OCD, and Calculated Amounts of Past Overburden for Pierre Shale Samples from H12

| SAMPLE DEPTH (ft) | SAMPLE ELEVATION (ft) (Above sea level) | $P_c$(tsf) min.-$P_c$-max. | $p_o'$(tsf) | OCR | OCD (tsf) | AMOUNT OF PAST OVERBURDEN (ft)[1] (using 2100' elevation datum plane) |
|---|---|---|---|---|---|---|
| 96 | 1984 | 150-168-244 | 3.2 | 53 | 165 | 4975 |
| 159 | 1921 | 194-214-248 | 5.2 | 41 | 209 | 6305 |
| 232 | 1848 | 117-145-258 | 7.7 | 19 | 137 | 4145 |
| 412 | 1668 | 147-163-274 | 13.6 | 12 | 149 | 4510 |
| 502 | 1578 | 141-198-211 | 16.6 | 12 | 181 | 5480 |
| 564 | 1516 | 150-178-258 | 18.6 | 10 | 159 | 4810 |
| | | | | average: | 167 tsf | average: 5040 ft. |
| | | | | | | use: 5000 ft. |

Surface elevation = 2080 ft.

$P_c$ = preconsolidation pressure (based on interpretation of U.S. Geological Survey tests)

$p_o'$ = (estimated) in situ vertical effective stress

OCR = overconsolidation ratio, $P_c/p_o'$

OCD = overconsolidation difference, $P_c - p_o'$

[1] Past overburden calculations based on assumption that entire sequence of sediments was continually acted upon by buoyant forces.

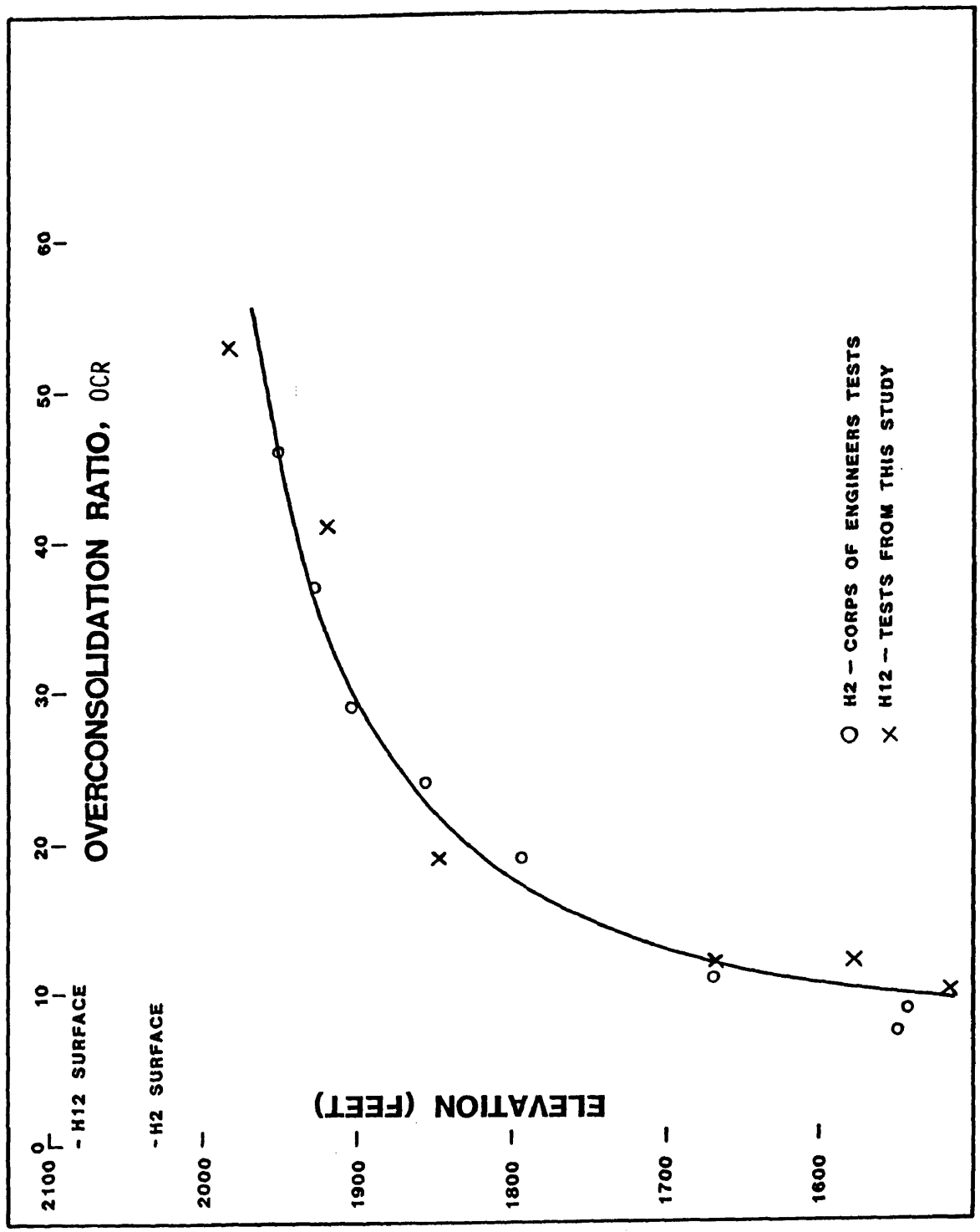
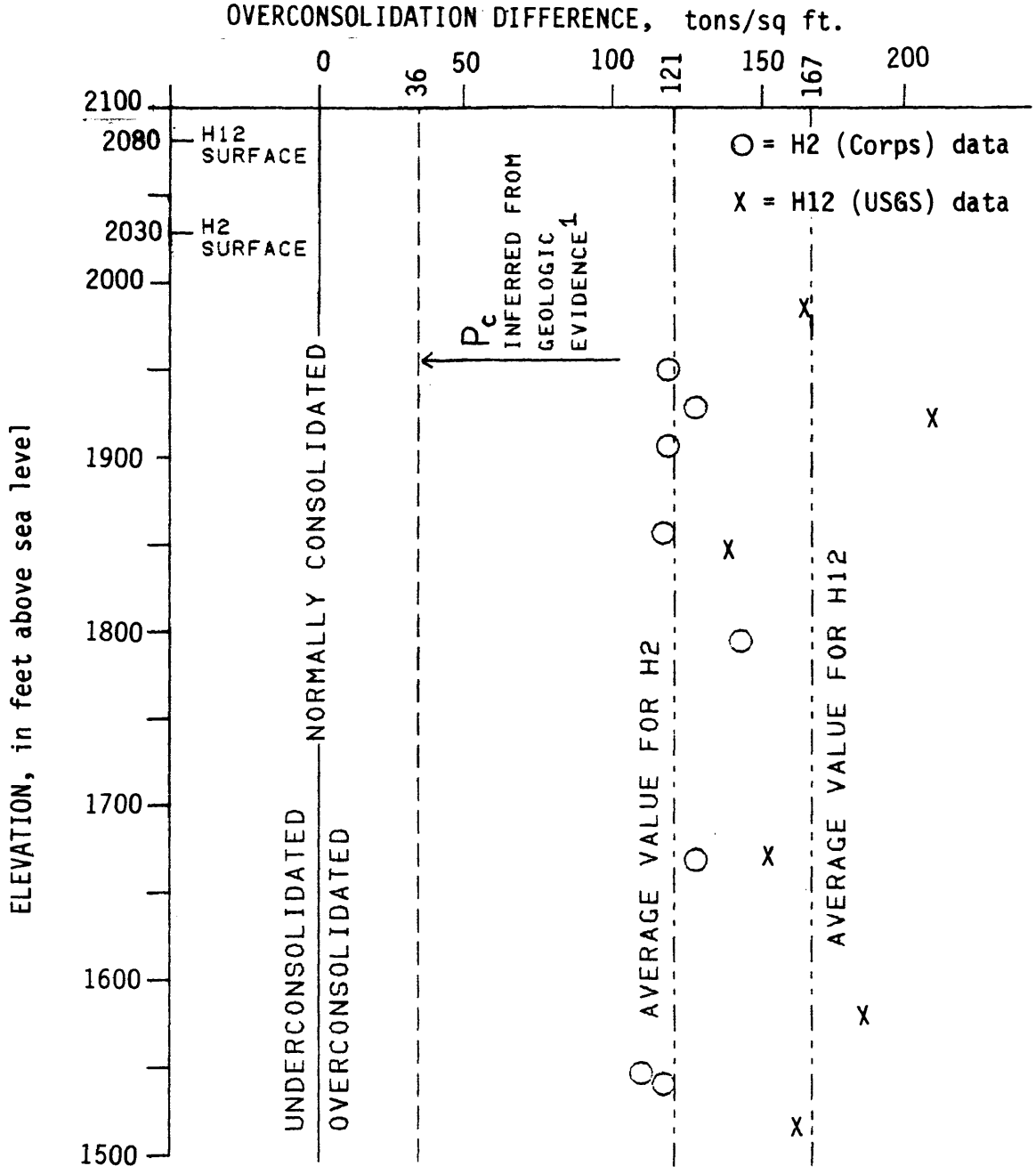



Figure 32 - OVERCONSOLIDATION RATIO VERSES DEPTH PROFILE.

and 3.5, these overburden thicknesses are based on the assumption that buoyant forces continually acted throughout the entire stratigraphic section.

Figure 33 shows the plot of overconsolidation difference (OCD) versus depth for both the Corps of Engineers and USGS tests. This diagram graphically illustrates the fact that the clay shale is over-consolidated. The average OCD values depicted for the H2 and H12 test samples, 121 and 167 tons/ft$^2$ respectively, are the same values reported in Tables 2 and 3. The values for the individual OCD data points and the corresponding overburden thicknesses can also be found in the tables. The dashed line at the OCD value of 36 tons/ ft$^2$ is discussed in Chapter 4. An analysis of why different $P_c$, or OCD, values were obtained for the Corps and USGS cores will not be presented here. Simply put, though, it is a reflection of differences in sampling and testing techniques for the two cores.

The graphical representations of consolidation state for the Pierre Shale at sites H2 and H12 (Figures 32 and 33) depict profiles that can be considered quite typical for a submerged sediment that is overconsolidated due to removal of overburden from an initially normally consolidated deposit (Olsen, Rice, Mayne, and Singh, 1986).




[1]NOTE - Conversion of geologically determined thickness of maximum past overburden to a preconsolidation pressure:

...used submerged unit weight of 65 lbs/cu ft, an average value (from unpublished Corps of Engrs. and USGS data).

...1100 ft x 65 lbs/cu ft ÷ 2000 = 35.8 tons/sq ft

Figure 33 - OCD VERSUS DEPTH PROFILE

Conceptually, Figure 34(b) shows the OCR varies with depth and increases dramatically near the ground surface, whereas Figure 34(c) shows the OCD is a constant with depth whose magnitude equals the buoyant weight of the overburden removed.

While the variation of OCR or OCD with depth has been investigated in previous studies, the variation of a maximum-past-overburden discrepancy with depth has not. The next chapter of this report will examine this issue.

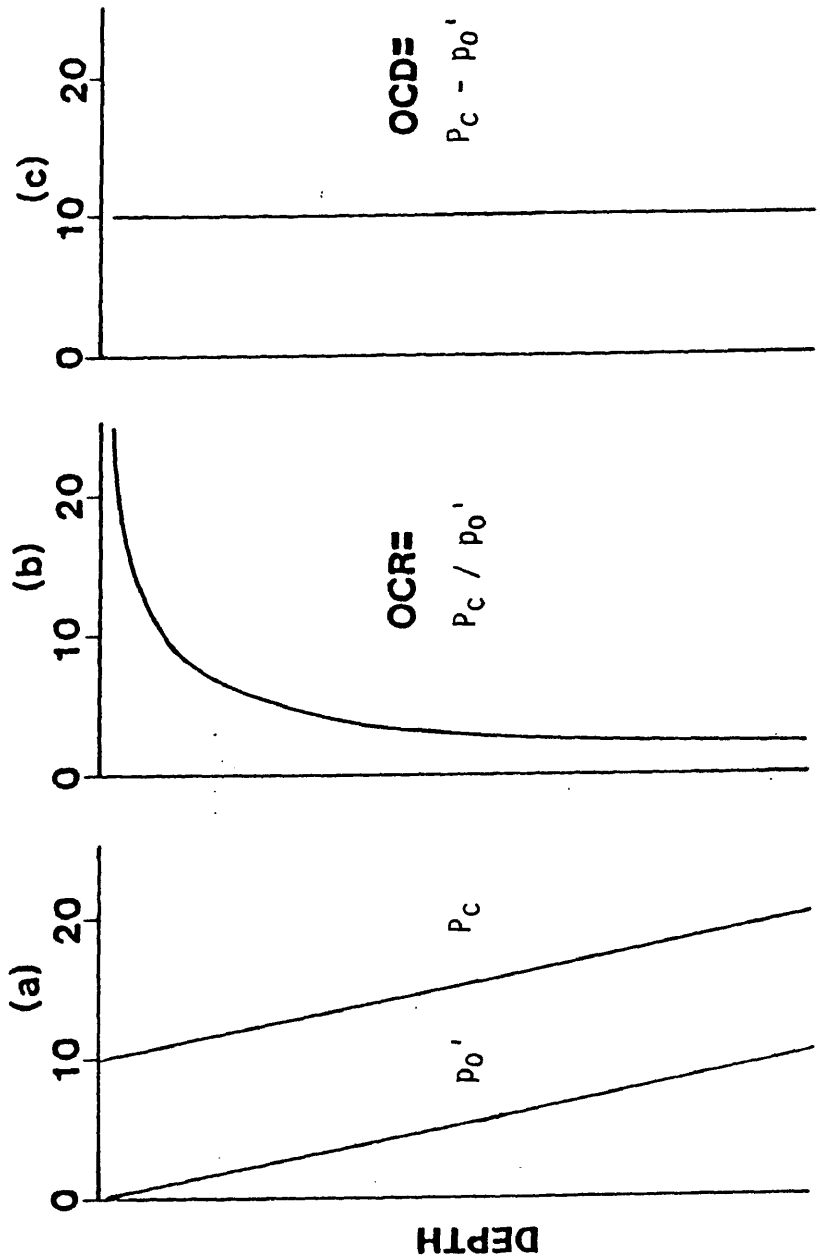



Figure 34 - CONCEPTUAL DIAGRAM SHOWING A COMPARISON OF OVERCONSOLIDATION DIFFERENCE (OCD) WITH OVERCONSOLIDATION RATIO (OCR) (Olsen, Rice, Mayne, and Singh, 1986).

# 4. COMPARISON OF GEOLOGICAL AND GEOTECHNICAL ESTIMATES OF MAXIMUM PAST OVERBURDEN

In this chapter, two tables are presented which allow for a comparison between geological and geotechnical estimates of maximum past overburden. In addition, one figure and an accompanying data table are presented which allow for an examination of the variation of the maximum-past-overburden discrepancy with depth — the discrepancy being that between the geological and geotechnical estimates of maximum thickness of past overburden.

Table 4 summarizes the values of maximum past overburden reported by other investigators who have made comparisons between geologically and geotechnically determined amounts of past overburden for the Pierre Shale and equivalent clay shales.

Table 5 compares the geotechnical and geological estimates made during this study. Figure 35 and Table 6 present the data that shows how the maximum-past-overburden discrepancy varies with depth. Figure 35 shows the plot of discrepancy ratio versus depth for both the H2 and H12 cores from Hayes.

TABLE 4 - Summary of Previous Investigators' Maximum-Past-Overburden Estimates for the Pierre Shale and Equivalent Clay Shales

| Clay Shale Formation | Source of Information | Thickness of Eroded Sediment (ft) (from geologic evidence) | $P_c$ (tons/ft$^2$) (from laboratory consolidation tests) range | aver.: | Thickness of Sediment[1] above $P_c$ Sample (ft) (from average $P_c$ value) |
|---|---|---|---|---|---|
| Bearpaw | Peterson (1954) | 2000-2500 | est. 100-150 | 125 | 3845 |
| Ft. Union | Smith (1953) | 1500 | 80-100 | 90 | 2770 |
| Colorado | Fleming and Others (1970) | 1900 | 110-130 | 120 | 3690 |
| Claggett | Fleming and Others (1970) | 1800 | 90-100 | 95 | 2925 |
| Bearpaw | Fleming and Others (1970) | 2200 | >100 | 100 | 3075 |
| Ft. Union | Fleming and Others (1970) | 950 | 65- 75 | 70 | 2155 |
| Pierre | Fleming and Others (1970) | 600 | 100-110 | 105 | 3230 |
| Pierre | McKown and Ladd (1982) | 1000 | 110-150 | 130 | 4000 |
| Pierre | McKown and Ladd (1982) | 1000 | 40-240 | | |
| | Same location as above. (from Geotechnical Engineers, Inc., 1977) | | 140 (Average)<br>165 (Average for majority) | | 4310<br>5075 |

[1] Calculations based on assumption that entire sequence of sediments was continually acted upon by buoyant forces.

Used: Submerged unit weight = 65 lbs/ft$^3$

TABLE 5 - Comparison of Estimates of Maximum Past Overburden for the Pierre Shale at Hayes, South Dakota

| METHOD | $P_c$ or OCD | FORMER THICKNESS OF SEDIMENT (ft) (using reference elevation of 2100 ft. above present-day sea level) |
|---|---|---|
| GEOLOGICAL: | | |
| Geologic Field Work from this Study | | Evidence for minimum of 600 ft.<br>More reasonable estimate: 800-1200 ft. |
| Harksen and Macdonald's Map (see Figure 5) | | 1100 feet |
| Most Reasonable | | 1100 feet |
| GEOTECHNICAL: | | |
| USGS Laboratory Consolidation Tests | 167 tsf | Assuming buoyancy: 5000 ft.<br>Assuming no buoyancy: 2550 ft. |
| Corps of Engineers Consolidation Tests | 121 tsf | Assuming buoyancy: 3600 ft.<br>Assuming no buoyancy: 1800 ft. |
| OCR vs. Depth Plot USGS Tests (see Figure 32) | 157 tsf | Assuming buoyancy: 4750 ft.<br>Assuming no buoyancy: 2400 ft. |
| OCR vs. Depth Plot Corps of Engr. Tests (see Figure 32) | 127 tsf | Assuming buoyancy: 3800 ft.<br>Assuming no buoyancy: 1950 ft. |
| Rounded Averages from Geotechnical Values | 143 tsf | Assuming buoyancy: 4300 ft.<br>Assuming no buoyancy: 2150 ft. |

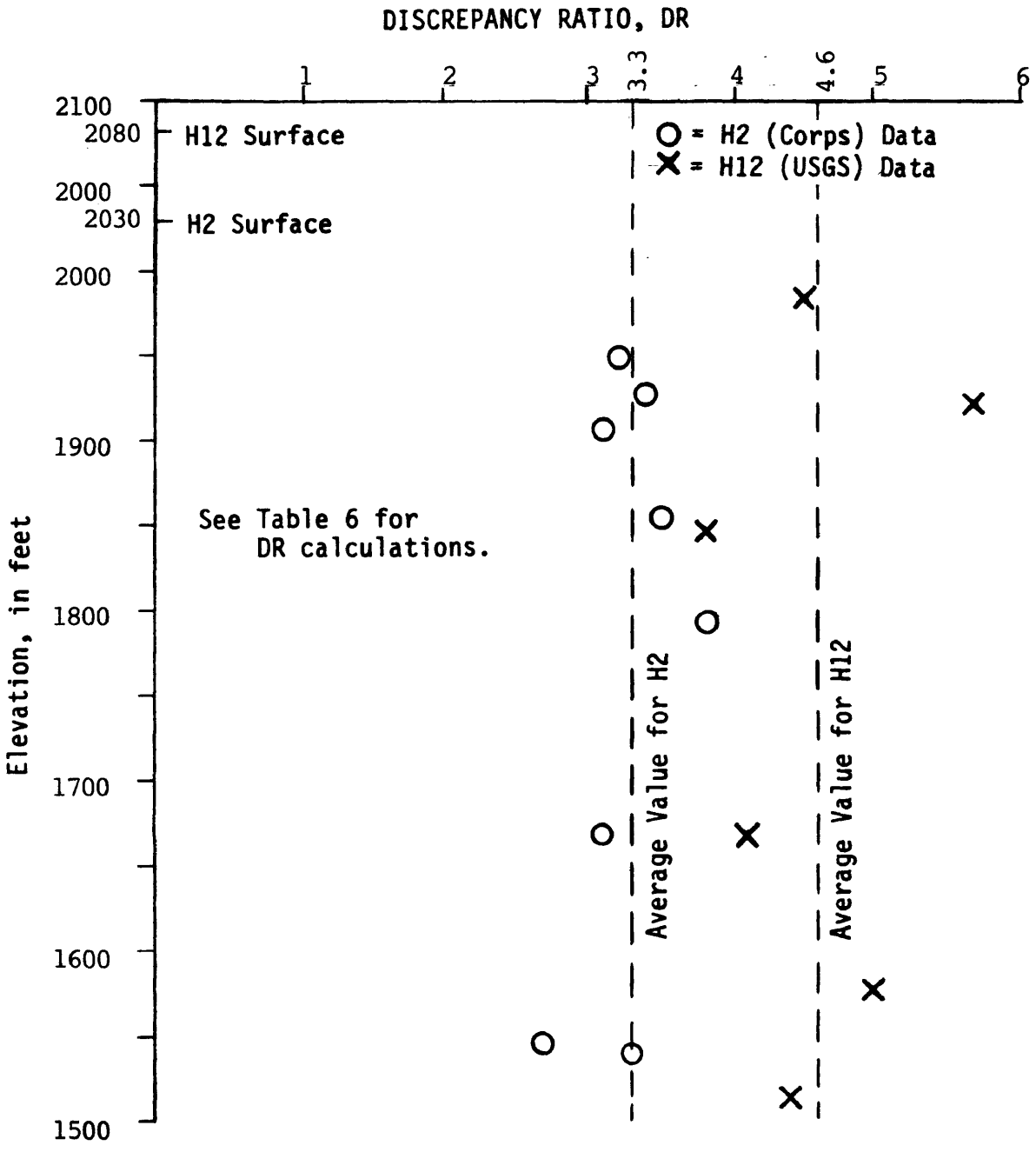



Figure 35 - DISCREPANCY RATIO VERSUS DEPTH PROFILE.

TABLE 6 - Discrepancy-Ratio Data for H2 and H12

$$\text{Discrepancy Ratio (DR)} = \frac{\text{Geotechnical Estimate}}{\text{Geological Estimate}}$$

H2
Corps of Engr. Tests

| Depth (ft) | DR |
|---|---|
| 80 | $\frac{3540'}{1100'} = 3.2$ |
| 102 | $\frac{3770'}{1100'} = 3.4$ |
| 125 | $\frac{3395'}{1100'} = 3.1$ |
| 175 | $\frac{3825'}{1100'} = 3.5$ |
| 235 | $\frac{4175'}{1100'} = 3.8$ |
| 362 | $\frac{3460'}{1100'} = 3.1$ |
| 482 | $\frac{2965'}{1100'} = 2.7$ |
| 488 | $\frac{3640'}{1100'} = 3.3$ |
| | average = 3.3 |

H12
USGS Tests

| Depth (ft) | DR |
|---|---|
| 96 | $\frac{4975'}{1100'} = 4.5$ |
| 159 | $\frac{6305'}{1100'} = 5.7$ |
| 232 | $\frac{4145'}{1100'} = 3.8$ |
| 412 | $\frac{4510'}{1100'} = 4.1$ |
| 502 | $\frac{5480'}{1100'} = 5.0$ |
| 564 | $\frac{4810'}{1100'} = 4.4$ |
| | average = 4.6 |

The discrepancy ratio (DR) is the ratio of the geotechnical estimate of maximum past overburden to the geological estimate. If the DR = 1, there is no discrepancy; if DR > 1, the geotechnical estimate exceeds the geological; and, if DR < 1, the geological estimate exceeds the geotechnical.

To evaluate whether or not a discrepancy is significant and warrants investigation, two things must be considered — the disrepancy ratio and the magnitude of the thickness estimates themselves. For a discrepancy in clay shales to be considered significant, one of the thickness estimates should exceed a thousand feet; and, secondly, the discrepancy ratio should be greater than or equal to 2, or less than or equal to 1/2.

By applying the above criteria to the estimates given by previous investigators (Table 4), only the Pierre Shale discrepancies would warrant investigation. The discrepancy ratio from the Pierre Shale estimates is 4 to 5 while the actual thicknesses are a thousand feet for all except the geologic estimate provided by Fleming.

An important explanation that needs to be given here concerns the manner in which the $P_c$ values have been converted to overburden thicknesses. The assumption has been made that buoyant forces acted throughout the entire

sequence (from surface on down) of the Pierre Shale and overlying sediment during and since the time of maximum thickness of past overburden. This assumption most certainly is not completely valid, but it is closer to the truth than the assumption that no buoyant forces have been present thereby allowing the total weight of all of the overlying material to be the consolidating load. The true answer would probably indicate that buoyant forces acted to some intermediate depth. Conventional geotechnical methods, however, would favor the assumption of buoyant forces acting throughout the entire sequence of sediment when the "intermediate situation" is not fully revealed to the investigator. An example follows which shows how much difference there would be between an overburden thickness value based on "total buoyancy" and one based on "no buoyancy."

For Core H2, Depth 488 ft:

a) unit weight pore water = 64 $lb/ft^3$
b) submerged unit weight = 62 $lb/ft^3$
c) total unit weight = 126 $lb/ft^3$
d) surface elevation = 2030 ft
e) reference elevation = 2100 ft
f) sample elevation = 1542 ft
g) difference (e-f) = 558 ft
h) preconsolidation pressure, $P_c$ = 130 $tons/ft^2$

Using submerged unit weight:

130 tons/ft$^2$ ÷ 62 lbs/ft$^3$ x 2000 = 4194 ft

4194 ft - 558 ft = 3636 ft ---> 3635 ft

Using total unit weight:

130 tons/ft$^2$ ÷ 126 lbs/ft$^2$ x 2000 = 2064 ft

2064 ft - 558 ft = 1506 ft ---> 1505 ft

Thus,

3635 ft versus 1505 ft.

The no-buoyancy situation produces values of overburden thickness equal to approximately one-half the thickness values calculated from the total-buoyancy situation. As indicated in Table 5, the values based on total unit weights (no-buoyancy) are closer to the geologic estimate of past overburden thickness (600 to 1100 feet); however, it should be stressed again that the no-buoyancy situation is not a realistic assumption.

The no-buoyancy values presented in Table 5 help show that regardless of whether a total-buoyancy or partial-buoyancy situation is used, a significant discrepancy in maximum-past-overburden estimates exists for the Hayes study site.

In the overconsolidation difference versus depth plot (Figure 33) of the previous chapter, the dashed line at 36 ton/ft$^2$ represents a stress value that was converted from the "most reasonable" of the geologically determined thicknesses of maximum past overburden. The conversion is based on the total-buoyancy assumption.

For the Hayes study site, the single value that best represents the geotechnically determined thickness of maximum past overburden is based on a preconsolidation pressure $P_c$ of 143 tons/ft$^2$. 143 tons/ft$^2$ converts to 4300 feet of overburden if the assumption is made that the entire sequence of sediments was continually acted upon by buoyant forces.

The value that best represents the geologically determined thickness of maximum past overburden at the Hayes site is 1100 feet. As mentioned before, for the total-buoyancy situation, 1100 feet of Pierre Shale overburden produces a vertical effective stress of 36 tons/ft$^2$.

The discrepancy ratio can be calculated from either the thickness values or the stress values. For the Hayes study site, the ratio of 4300 feet to 1100 feet, or 143 tsf to 36 tsf, produces a DR equal to 4. This is a significant discrepancy.

To examine the discrepancy versus depth issue, the DR was calculated for each sample used in the Corps of Engineers and USGS tests. The geotechnically determined overburden thickness values used in calculating the DR's were the ones shown in Tables 2 and 3. The geologically determined thickness used was 1100 feet.

The discrepancy ratio versus depth plot is shown in Figure 35; Table 6 contains the data used for making the plot. Predictably, the data points produce a profile that is exactly the same in appearance as the overconsolidation difference (OCD) versus depth profile of Figure 33. This occurs because, in the calculation of DR, the geologic thickness (denominator) of the eroded material is the same regardless of sample depth, while the geotechnical thickness (numerator) is based on the OCD for a particular depth; thus, DR varies according to OCD. Since OCD values are simply $P_C$ values that have been adjusted to the ground surface, and theoretically should not change within an homogenous lithology, their variation with depth is a reflection of differences in the test samples and/or testing techniques, as mentioned in Section 3.6. If the two thicknesses, used in calculating the DR, had the present-day amount of overburden (depth to sample) added to them, then the DR with depth would asymptotically approach

the value of 1. Thus, if DR values are calculated based solely on the eroded thickness of overburden, as has been done in this study, then minor mathematical variation is avoided in the smoothed profile of DR versus depth.

# 5. ASSESSMENT OF POSSIBLE DISCREPANCY-CAUSING FACTORS

## 5.1 Chapter Introduction

A discrepancy has been shown to exist between the geological and geotechnical determinations of maximum past overburden for the Pierre Shale at Hayes, South Dakota. An assessment of the factors causing the discrepancy involves, primarily, an analysis of the geotechnical determination and not the geological. In other words, the geotechnical estimate of past overburden thickness is generally recognized as being too high rather than the geological estimate being too low. Because a problem exists in the geotechnical estimate, an analysis of the principal factors influencing the determination of $P_c$ from laboratory consolidation tests is made in order to resolve the discrepancy. This analysis involves geologic factors as well as laboratory factors.

## 5.2 Geologic Factors

Of the numerous geologic or environmental mechanisms that have been described as factors in causing soils to be, or appear to be, overconsolidated (Brumund, Jonas, and Ladd, 1976), only two warrant serious examination as major contributors to the high $P_c$ values exhibited by the

Pierre Shale. These two mechanisms are cementation and delayed consolidation. There is a third geologic factor that is important with respect to developing elevated preconsolidation pressures — removal of overburden. Since the first half of this report was geared toward demonstrating that erosion has occurred at the Hayes study area (but not enough erosion to account for the observed high $P_c$ values), there will be no further discussion about it here.

### 5.2.1 Cementation

An analysis of the effects of cementation on the compressibility of Pierre Shale was performed by McKown and Ladd (1982). The shale samples they examined came from northeast Nebraska along the Missouri River near the South Dakota border. Their study investigated the possible effects of carbonate cementation on the compressibility and apparent maximum past pressure of the Pierre Shale by 1) performing one-dimensional consolidation tests on specimens with and without leaching to remove some of the calcium carbonate, and 2) correlating values of maximum past pressures estimated from consolidation tests previously performed on specimens of Pierre Shale with the amount of calcium carbonate content present in the test specimens.

In summary, they found:

> "1. The results support the conclusion from previous research that natural cementation of cohesive soils can have a significant effect on the apparent maximum past pressure estimated from consolidation test data.
>
> 2. Relatively small amounts of calcium carbonate, above a threshold value of about 2 percent by weight, appear to cement the structure of this Pierre Shale, causing apparent maximum past pressures up to two to three times the estimated maximum past overburden stress. However, $CaCO_3$ contents in excess of this threshold value (even up to 50 percent or more) produce little further increase in the apparent maximum past pressure.
>
> 3. Reduction of the $CaCO_3$ content of a clay-shale specimen due to leaching with a HCl solution, from about 17.0 percent to about 12.5 percent by weight, caused an increase in compressibility during recompression and a lower measured apparent maximum past pressure."

McKown and Ladd's study indicates calcium carbonate can be a significant factor in increasing the $P_c$ values of Pierre Shale. Thus, if the $P_c$ is increased by cementation, then the maximum-past-overburden discrepancy is also increased. The data presented by McKown and Ladd does not lead this author to conclude that a definitive statement can be made regarding a 2 percent threshold value, nor that cementation can be given complete credit for the observed high values of $P_c$. No conclusions have

been drawn by this author regarding the possible effects of calcium carbonate cementation on the maximum past pressure of the Pierre Shale at Hayes, South Dakota. The fact that carbonate minerals exist in the Pierre Shale at Hayes was verified by x-ray diffraction of eleven samples that came from various depths at core site H12 (Table 7). The carbonate minerals present include siderite ($FeCO_3$), dolomite ($MgCO_3$), and calcite ($CaCO_3$). Whether or not this carbonate material is a cementing agent within the clay shale is not known. The carbonate percentages shown in Table 7 are by volume, whereas McKown and Ladd's were by weight. Also, these volume percentages are approximate values with margins of error greater than 2 percent (verbal communication with T. C. Nichols, USGS, Denver, CO).

TABLE 7 - Percent Carbonate (by Volume) for Pierre Shale Samples from Core Site H12 near Hayes, South Dakota

| Depth (ft) | Carbonate % | % $FeCO_3$ | % $MgCO_3$ | % $CaCO_3$ |
|---|---|---|---|---|
| 78 | 7 | 0 | 0 | 7 |
| 106 | 21 | 0 | 1 | 20 |
| 157 | 7 | 0 | 0 | 7 |
| 207 | 10 | 0 | 0 | 10 |
| 255-260 | 0 | 0 | 0 | 0 |
| 305-310 | 24 | 12 | 0 | 12 |
| 358 | 1 | 0 | 1 | 0 |
| 405-410 | 2 | 0 | 2 | 0 |
| 456.5 | 1 | 0 | 0 | 1 |
| 508 | 2 | 0 | 1 | 1 |
| 559 | 2 | 0 | 0 | 2 |

### 5.2.2 Delayed Consolidation

A mechanism which may have played a significant role in developing the high degree of overconsolidation observed in the Pierre Shale, but which is difficult to assess, is delayed consolidation.

When a soft clay is subjected to a constant consolidation pressure, the resulting deformations may be divided into three parts. They are (from Mitchell, 1967):

1. Immediate compression due to compression of gas in partly saturated clays and shear deformation at constant volume;
2. Primary consolidation, the rate of which is controlled by the rate of dissipation of excess pore water pressure; and,
3. Delayed compression that involves a time-dependent adjustment of the soil structure.

In essence, delayed compression refers to the change in void ratio that occurs in a soft clay while under a constant effective stress. In some normally consolidated clays it has been found that delayed compression forms the greater part of the total compression under applied pressure. Bjerrum (1967) showed that such clays have gradually developed a reserve resistance against further compression as a result of the considerable decrease in

void ratio which has occurred under constant effective stress, over the hundreds or thousands of years since sedimentation. These clays, although normally consolidated, appear to be overconsolidated as indicated by the $P_c$ to $p_o'$ relationship.

The geological history and compressibility of an overconsolidated clay is depicted in Figure 36. As shown, the original consolidation and aging was under effective overburden pressure $p_1$. Reduction of the overburden pressure to $p_o$ by erosion then occurred, giving an overconsolidation ratio $p_1/p_o$. When the clay is reloaded, compression will be small until pressure $p_2$ is reached, at which point a break in the curve is observed and virgin compression resumes. $p_1$ represents the "true" $P_c$ for the clay while $p_2$ represents the estimated $P_c$ as determined from a laboratory consolidation test. Assuming $p_1$ is supported by field evidence, then the discrepancy between maximum-past-overburden estimates is represented by $p_2-p_1$.

The curves in Figure 36 are based on data collected by Bjerrum on specific Norwegian soft-clays of less than 10,000 years in age. No attempt was made by this author to use the Norwegian data (in those limited cases where void ratio values were marked on Bjerrum's e-log p curves) for the purpose of extrapolating a $P_c$ value for the Pierre Shale. Any attempt to do so would produce very

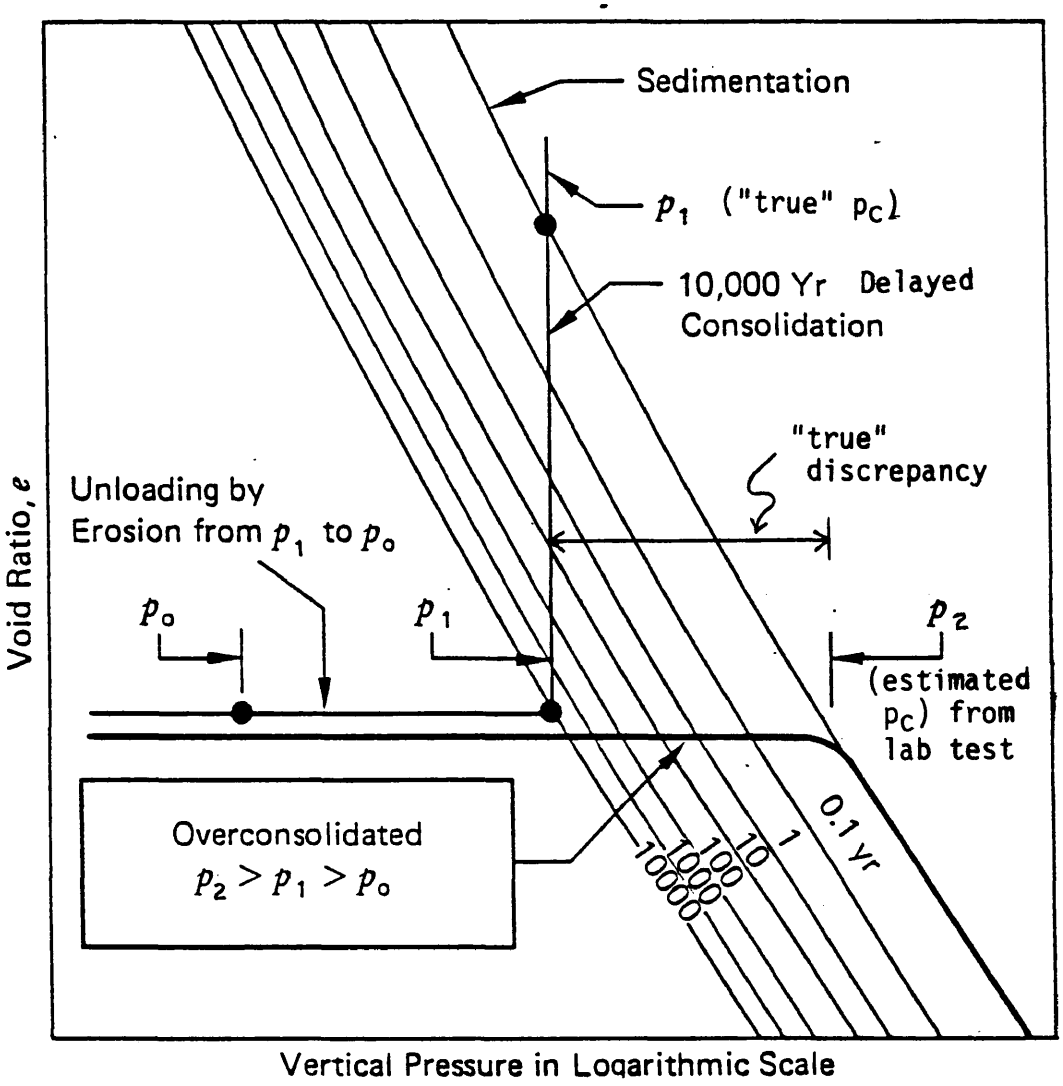



Figure 36 - GEOLOGICAL HISTORY AND COMPRESSIBILITY OF AN OVERCONSOLIDATED CLAY (modified from Bjerrum, 1972).

tenuous results at best. The only similarity between the two materials is particle size; they both are comprised primarily of clay-sized particles.

When the Pierre Shale data is examined in light of the Norwegian data, Bjerrum's curves should only be considered "conceptual." This concept would appear to be applicable to the Pierre Shale since it too was once a soft clay of young age. Seventy million years (the age of the Pierre) should produce a significant amount of delayed consolidation (reduction in void ratio) with corresponding high $P_c$ values and a major maximum-past-overburden discrepancy.

## 5.3 Laboratory Factors

According to Brumund and others (1976), the three most important factors influencing the determination of $P_c$ from laboratory consolidation tests are sample disturbance, load increment ratio, and load increment duration. Brumund's studies were done on clay soils, sometimes sensitive clay soils.

Where possible, each of the three factors was examined for both the Corps of Engineers and USGS tests of this study. The findings supported Brumund's conclusions concerning the effects on $P_c$, which, in simple terms,

say that any departure from ideal test conditions (involving the three factors) causes the e-log p plot to shift in a manner which lowers the estimated value of $P_c$, at least from the Casagrande construction.

Since a lowering of $P_c$ values reduces the maximum-past-overburden discrepancy, no further discussion or analysis of these laboratory factors is warranted, considering the need involves finding factors that cause the $P_c$ values to be increased.

## 5.4 Chapter Conclusions

Although somewhat by default, the only mechanisms that can be used as possible explanations for the observed high values of $P_c$ and the correpsonding high maximum-past-overburden discrepancy are cementation and delayed consolidation.

# 6. REPORT CONCLUSIONS

As a result of this study on estimates of maximum past overburden for the Pierre Shale in the Hayes area of South Dakota, the following conclusions have been reached.

1. Geotechnical estimates of the maximum thickness of past overburden indicate that approximately 4300 feet (1311 m) of material has been eroded away above a reference elevation of 2100 feet at Hayes, South Dakota. Geological estimates indicate that approximately 1100 feet (335 m) of material has been eroded away.
2. The geotechnically determined maximum thickness of past overburden is approximately four times the geologically determined thickness. This discrepancy is significant.
3. In this report, "significant discrepancy" has been defined in non-statistical terms; the term "discrepancy ratio (DR)" has been introduced; and the variation of the discrepancy with depth has been examined. A significant discrepancy exists when 1) one of

the thickness estimates exceeds a thousand feet, and 2) the discrepancy ratio is greater than or equal to 2, or less than or equal to 1/2. The discrepancy ratio is the ratio of the geotechnical estimate of maximum past overburden to the geological estimate. The variation of the discrepancy ratio with depth is consistent with the variation of overconsolidation difference (OCD) with depth provided 1) the geological estimate does not vary, and 2) both the geological and geotechnical estimates are values adjusted to a common surface datum plane.

4. The discrepancy could be accounted for, in part, if the assumption is made that buoyant forces were totally lacking at some time during the history of the sedimentary sequence. However, this is a completely unrealistic assumption.

5. To assess the cause of the discrepancy the assumption was made that the geologically determined value of maximum thickness of past overburden was essentially correct. This left the geotechnically determined

value to be examined for errors; or, in other words, the possible mechanisms that could cause an elevated $P_C$ value were examined.

6. The laboratory factors that can affect the determination of $P_C$ all tend to lower the $P_C$ value; thus, they were ruled out as possible explanations for the discrepancy. For the Pierre Shale, the geological mechanisms that can affect $P_C$ and which could be assessed, qualitatively, are cementation and delayed consolidation. Studies by other investigators suggest that either mechanism by itself, or the two together, could account for the high $P_C$ values of the Pierre Shale and, further, be an explanation for the maximum-past-overburden discrepancy.
7. Future geotechnical studies in the Pierre Shale in central South Dakota that involve $P_C$ determinations should focus on trying to quantitatively determine the amount of cementation and delayed consolidation that has occurred. Although more work needs to be done on it, cementation in the Pierre

Shale has been studied by others; therefore, the emphasis of future studies should be on delayed consolidation.

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