MASTER

THE
HYDROLOGIC PROPERTIES
OF
SHALE
AND RELATED ARGILLACEOUS ROCKS

Report prepared under
Contract: LLL 590-5909

By A. N. Moiseyev,
Department of Geological Sciences
California State University, Hayward

Nov. 15, 1979

FOREWORD

This report presents the results of a bibliographic search which was designed to collect information on the hydrologic properties of shale and related argillaceous rocks. Its prime objective was the gathering of numerical data to serve as reference for studies into the use of such rocks as repositories for radioactive wastes. The tables in which these data have been compiled thus represent the main part of this report.

During the search additional information was uncovered and judged to be relevant to the scope of the project. Mathematical relationships between the various rock parameters (porosity, permeability, density, depth, etc.) were thought to be useful for making estimates whenever data is incomplete and for designing mathematical models of repositories. Likewise, it was decided that possible relationships between shale mineralogy and hydrologic behavior, though poorly backed by numerical data, should be mentioned mainly as reference for future search. Finally, it was deemed that the numerical data would be made more practical if supported by a few general definitions and regional geologic information.

DISCLAIMER

This report was prepared for the U.S. Atomic Energy Commission, Office of the General Manager, by the U.S. Geological Survey, under contract number 14-01-00-0001-1000. The U.S. Geological Survey is not responsible for the accuracy or completeness of the information contained herein, nor for any errors or omissions that may appear in this report. The U.S. Geological Survey is not responsible for the accuracy or completeness of the information contained herein, nor for any errors or omissions that may appear in this report.

This report does not pretend to cover fully the complex hydrologic problems of shale. Rather, the background information is presented in a form to make it understandable for the non-specialist. Probably, most of it could be omitted if the report became incorporated into a larger and more specialized document. The bibliographic search was carried out with the intent of covering as wide a spectrum of references as possible over the 2 1/2 months period allocated to the project. Unavoidably, some references must have been missed, particularly those from reports or periodicals of limited distribution and those from recent publications which have not yet been listed in bibliographic files. Data search was accomplished by two half-time supervised graduate students using the accessible files of the libraries at the University of California in Berkeley and the Lawrence Berkeley Laboratory, at the U.S. Geological Survey in Menlo Park and at the California Division of Mines and Geology in San Francisco.

CONTENTS

	Page
I. INTRODUCTION	1
II. THE GEOLOGIC PROPERTIES OF SHALES	3
1-Definitions	3
2-Mineralogy	6
3-Environments of Deposition	10
4-Diagenesis of Shales	12
5-Post Diagenetic Changes	17
6-Major Shales occurrences in the United States	17
III. THE HYDROLOGIC PROPERTIES OF SHALES	21
1-Brief Review of Important Definitions	21
2-Mathematical Relationships	25
3-Lithologic Parameters	30
4-Diagenetic and Post Diagenetic Changes	31
IV. THE HYDROLOGIC PROPERTIES OF SHALES IN THE UNITED STATES	36
Organization of Data	36
Region 1: Pacific Coast, Great Valley, Great Basin	38
Region 2: Rocky Mountains, Colorado Plateau, and Great Plains	74
Region 3: The Mid-Continent	103
Region 4: The Gulf Coast and the Mississippi Embayment	120
Region 5: The Appalachian and Great Lakes	136
Region 6: The Atlantic Coastal Plain and the Triassic Basins	147
V. BIBLIOGRAPHIC REFERENCES	156

LIST OF FIGURES

Figure	Page
1. Permeability/Porosity relationships calculated for various mathematical models	28
2. Effect of ion adsorption upon the permeabil- ity of two clay minerals: smectite and kaolinite	33
3. Map showing the location of regions where shale units are found in the United States	37
4. Map showing the location of the Cambrian Terrigenous Sequence in the Great Basin .	39
5. Map showing the location of the Eleana Formation (Upper Devonian-Mississippian) in the Great Basin	41
6. Generalized section across the San Joaquin Valley	43
7. Generalized section across the Sacramento Valley	44
8. Stratigraphic relations of the Pierre shale and equivalent rocks	75
9. Structure sections showing typical relation- ships in the Colorado Plateau and the Rocky Mountains	77
10. Distribution of Paleozoic structures in the Mid-Continent	104
11. Map showing the distribution of the Chattanooga Shale (Devonian-Mississippian) in the United States	104
12. Sections illustrating structural relation- ships in the Mid-Continent	105
13. Section across the Gulf Coast clastic wedge	121

LIST OF FIGURES (Continued)

Figure	Page
14. Stratigraphic diagram showing the relationships between the Martinsburg and Chattanooga shales in the Appalachian-Great Lake Region	137
15. Generalized structural sections across the Appalachians and the Atlantic Coastal Plain	148
16. Section showing detailed structure of a Triassic Basin	148

LIST OF TABLES

Table	Page
4-1-a. Summary of Paleozoic rocks in the Great Basin	45
4-1-b. Summary of rock units in the San Joaquin Valley area, California	46
4-1-c. Summary of rock units in the California Coast Ranges	48
4-2. Summary of rock units in the Rocky Mountains, Colorado Plateau and Great Plains	78
4-3. Summary of rock units in the Mid- Continent Region	106
4-4. Summary of rock units in the Gulf Coast and the Mississippi Embayment Region .	122
4-5. Summary of rock units of the Appalachian- Great Lakes Region	138
4-6. Summary of rock units in the Atlantic Coastal Plain and Triassic Basins Region	149

LIST OF HYDROLOGIC DATA

Data	Page
Region 1: Pacific Coast, Great Valley, and Great Basin	51
Region 2: Rocky Mountains, Colorado Plateau, and Great Plains	80
Region 3: Mid-Continent Region	112
Region 4: Gulf Coast and Mississippi Embayment .	124
Region 5: Appalachian-Great Lakes Region	142
Region 6: Atlantic Coastal Plain and Triassic Basins	151

ABSTRACT

This report is the result of a bibliographic study designed primarily to collect hydrologic data on American clay-rich rocks. In connection with this search the following information was also sought: stratigraphy, environment of deposition, mineralogic composition, and diagenetic changes. The collected numerical data are presented in tables which contain densities, porosities, and/or hydraulic conductivities of approximately 360 samples. Additional data include hydraulic diffusivities, resistivities, flow rates, and rock strengths. Geologic information suggests that large deposits of shale which may be suited for waste repository belong to all ages and were formed in both marine and continental environments. Of the studied units, the most promising are Paleozoic in the eastern half of the country, Mesozoic in the central part, and Cenozoic in the Gulf Coast area and the West. Less widespread units locally present some additional possibilities. Mineralogic investigations suggest that the smectite content in rocks shows a decrease in time (70% in Recent rocks; 35% in pre-Mesozoic rocks). Because of this predominance of smectite in younger rocks, the modeling of repositories in post-Paleozoic formations might require knowledge of additional and poorly known parameters.

Results of investigations into the mathematical relationships between porosity and permeability (or hydraulic conductivity) suggest that in situ permeabilities could be estimated from sonic logs and fluid pressure changes at depth.

This work was supported by the United States Nuclear Regulatory Commission under a Memorandum of Understanding with the United States Department of Energy.

SUMMARY

The investigation described in this report was carried out to obtain numerical data which could be used for assessing possible repositories of radioactive wastes in shale. The gathering of information was accomplished through a bibliographic search of the files of the University of California at Berkeley, of the Lawrence Berkeley Laboratory, of the U.S. Geological Survey in Menlo Park, and of the California Division of Mines and Geology in San Francisco.

The search was completed between June 13 and September 1, 1979. Two graduate students from the California State University, Hayward, each working half time were directed to collect data from references listed in the GEOREF computer file and additional sources furnished by the principal investigator. Weekly meetings were organized during which the students reported their findings, discussed their problems, and received new instructions for further search. The gathering of numerical information was phased out in the first part of August when it appeared that the search was yielding few additional data. Work was redirected for the remaining allocated time to the collecting of geologic background information (stratigraphy, thicknesses, structure, etc.) in support of the hydrologic data.

The main findings of the investigation are contained in tables at the end of the report. They are arranged geographically into 6 areas: 1-Pacific Coast and Great Basin; 2-Rocky Mountains, Colorado Plateau, and Great Plains; 3-Mid-Continent; 4-Gulf Coast and Mississippi Embayment; 5-Appalachians and Great Lakes; and 6-East Coast and Triassic Basins. Each region contains a brief account of the geologic history, a stratigraphic table listing formation names, thicknesses, and lithology, and a table of hydrologic properties. The following findings are listed: Region 1-Vertical and horizontal conductivities of Recent to Pliocene shale; Region 2-Density, porosity, and conductivity of continental Eocene shale (Green River and Uinta formations) and marine Cretaceous shale (Pierre and related shales); Region 3: density and porosity of Pennsylvanian shale; Region 4: porosity and density of Cenozoic to Pennsylvanian shales; Region 5: density, porosity and electrical resistivity of Paleozoic shales; and Region 6: density, porosity, conductivity, and diffusivity of Miocene to Triassic shale.

Additional geologic findings indicate that shales are predominantly composed of kaolinite, smectite, and illite (more commonly mixed illite/smectite layers) which change during burial. Clays which have not been buried below

1,400 m are rich in smectite, those which underwent burial to depths between 1,400 m and 3,800 m show progressive depletion in smectite (down to 20%), and those which reached depths in excess of 7,500 m are totally depleted in both smectite and illite. These changes are paralleled by a progressive disappearance in potassium feldspar, calcic plagioclase, and kaolinite. Age-related variations in smectite content have also been observed: Recent shale averages 70% smectite in mixed layers, Cenozoic and Mesozoic clay contains between 70% and 35% smectite, and pre-Mesozoic mixed layer clays contain 35% or less smectite. By its variable ion-exchange and adsorption properties smectite has great influence upon the hydrologic properties of shale. Effects can be considerable, but more work is needed before they can be reliably predicted. In the present state of knowledge permeability of smectite-rich shale is likely to have the most unpredictable long-term behavior. Mathematical relationships have been proposed to relate permeability and porosity of shale. However, most fail to make accurate predictions probably because shale permeability measured directly on cores and drill holes is marred by the fissuring of boring tools. So far, the most successful results have been obtained from data derived from sonic logs and variations in pore

pressures. The method, however, has not been properly tested for porosities below 10% and permeabilities below 10^{-6} darcys.

INTRODUCTION

The aim of this report is: 1- To provide a data compilation of the permeabilities (or hydraulic conductivities), porosities, densities, and a few additional physical parameters of shale; 2- to provide a general outlook of the relationships which exist between these parameters; and 3- to outline areas where more search is needed for a better prediction of long-term behavior of waste repositories in shale.

Shale and related rocks, siltstone, mudstone, and claystone belong to a group of broadly represented relatively impervious rocks which offer some potential for long-term storage of radioactive wastes. Hydrologically, they are characterized by the uncommon combination of high porosity and low permeability which is related in part to their very fine grain-size. Their low permeability results in a scarcity of hydrologic data: neither oil companies nor hydrologists have been particularly eager to take measurements in rock of low economic importance. In addition, estimates of shale permeabilities in the subsurface by producing fluids from wells are difficult because shale normally produces no fluid. However, in the last decade the interest in shale as a hydrocarbon source

has stimulated research. The list of available data is steadily growing, and it is likely that the tables of numerical parameters which are presented in this report will need updating in a foreseeable future.

GEOLOGIC PROPERTIES OF SHALE

1- DEFINITIONS

Shale is the generic name given to the widespread group of sedimentary rocks which is characterized by a predominance of silt and clay-size fractions. Variations in textures and structures are used to define specific rock names. Shale "proper", mudstone, siltstone, and claystone are the most common types.

The following definitions are quoted directly from the Glossary of Geologic Terms (AGI, 1972). These are important to know as names given in the literature do not always have the same meaning.

Shale

"A fine-grained, indurated, detrital sedimentary rock formed by the consolidation (as by compression or cementation) of clay, silt, or mud and characterized by finely stratified (laminae 0.1-0.4 mm thick) structure and/or fissility that is approximately parallel to the bedding (along which the rock breaks readily into thin layers) and that is commonly most conspicuous on weathered surfaces, and by a composition with an appreciable content of clay minerals and with a high content of detrital quartz; a thinly laminated or fissile claystone, siltstone or mudstone." ... "The term 'shale' is regarded sometimes as a

structural term with the significance of thin bedding or fissility and without implying a particular composition: it has been loosely applied to massive or blocky indurated silts and clays that are not laminated, to laminated silts and clays that are not indurated, to fine-grained and thinly laminated sandstones, and to slates."

Mudstone

"(a) An indurated mud having the texture and composition, but lacking the fine lamination or fissility, of shale; a mucky or massive, fine-grained sedimentary rock in which the proportions of clay and silt are approximately the same; a non-fissile mud shale."..."(b) A general term that includes clay silt, claystone, siltstone, shale, and argillite, and that should be used only when the amounts of clay and silt are not known."

Siltstone

"An indurated or somewhat indurated silt having the texture and composition, but lacking the fine lamination or fissility, of shale: a massive mudstone in which the silt predominates over clay: a non-fissile shale. Pettijohn regards siltstone as a rock whose composition is intermediate between those of sandstone and shale and of which at least two-thirds is material of silt size."

Claystone

"An indurated clay having the texture and composition, but lacking the fine lamination or fissility, of shale: a massive mudstone in which the clay predominates over silt; a non-fissile clay shale."

Other Types of "Shales"

Just about any type of fine-grained sedimentary rock exhibiting laminations has been called "shale" by some field geologists. One example is Monterey Shale, a Miocene formation of Coastal California. Locally this rock is a finely layered diatomite entirely composed of siliceous remains of diatoms with minimal amounts of clay. Another example is Oil Shale, a hydrocarbon-rich member of the Green River Formation (Middle Eocene) of Utah and Wyoming. This rock is unusually rich in calcium carbonate and should be referred to as marl or marlstone, a European term sometimes used for rocks containing clay and calcite with minor amounts of other constituents.

In summary, the term "shale" has been applied indiscriminately to very diverse rocks: massive or finely layered, indurated or soft, rich or devoid of clay minerals, fissile or not, etc. This abusive labelling practice has led to the inclusion of sedimentary rocks of widely different origins in one single category. Unfortunately, by looking

through a list of references it is not always possible to determine the actual meaning implied by an author. This explains some of the wide range of variation in the hydrologic property of shale; for example, the hydraulic conductivity which spans over ten orders of magnitude.

2- MINERALOGY

A close relationship exists between the hydrologic properties of shale and its mineral content. It would seem, at first glance, that a good characteristic of shale is its high clay content and that the hydrologic properties would be related to the predominance of one clay mineral over the others. Although true in general, this statement is only partially correct because geologists have used the term "clay" to designate both a family of layered silicate minerals and a very fine grain-size (less than 4 microns). It is true that most clay minerals are in the clay-size range, but other minerals, particularly quartz, are sometimes found in the clay fraction. The Monterey Shale (Miocene) of California, already mentioned, is sometimes made up entirely of clay-size siliceous fragments. Another classic example is glacial "clay", a rock flour generally composed of nearly unaltered clay-size rock fragments. With this confusion, further compounded by the problems of definitions discussed earlier, there can be little doubt

that the wide spectrum of hydrologic properties observed in shale is partly due to semantics. In order to minimize any sources of error, "clay" will be restricted in this report to mean clay minerals and "clay-size" to mean a size fraction less than 4 microns.

Clays

It would be beyond the scope of this report to give a complete mineralogic description of the most important constituents of shale. Only the general types of clays will be outlined here, and characteristics which affect the hydrologic properties will be emphasized. The interested reader can find additional information in references such as Weaver (1959) and Weaver and Pollard (1975). The clay minerals which are found in shale belong to the following types:

Kaolinite has a simple two-layer structure with little affinity for ionic exchange and adsorption. This clay somewhat lacks plasticity.

Illite. This mineral has a three-layer structure characterized by some replacement of Si^{4+} by Al^{3+} combined with an addition of K^+ on the outside of the structure. This clay, sometimes called hydromuscovite, has moderate ion exchange properties, moderate adsorption affinities, and a variable plasticity.

Smectite is another three-layer clay characterized by replacement of Si^{4+} by Al^{3+} . In this case, however, electronic unbalance is compensated by the addition of various ions (Mg, Fe, Zn, etc.) in the vacant octahedral sites inside the structure. Clays of this type have extreme variations in plasticity and ion exchange capabilities (swelling clays can absorb enormous amounts of fluids) and their physical properties are greatly affected by the nature of ions adsorbed. Na ions make them sticky and plastic when wet; Ca ions make them less sticky and less prone to adsorb water. Quite expectedly, ion exchange also affects the hydrologic properties of shale and explains why some smectite rich rocks can behave as semi-permeable membranes (Berry, 1959). Other names used for minerals of this type are montmorillonite (when used in a generic sense) and bentonite.

Chlorites have composite structures which can be regarded as derivatives of kaolinite structure or as two illite structures tied by Mg^{2+} instead of K^{+} . Rich in iron and magnesium, they lack the swelling properties of smectite.

Mixed layer clays are combinations of two types of clays in a large structure. In some instances the layers follow an orderly pattern, in others they are random. The mixed illite/smectite layer clay is an important constituent of

shale. Its properties are greatly dependent upon the content in smectite layers, but as a whole, they are intermediate between those of the two end members.

Other types. Among the less important clay constituents of shale are sepiolite, attapulgite, and hallophane.

Many clay minerals are very sensitive to prevailing physical and chemical conditions. Their relative abundance changes during burial in response to new pressure-temperature conditions and perhaps also to the duration of the burial process.

Non-Clay Constituents

Feldspars are common clastic constituents of shale, particularly in the silt-size fractions. Calcic plagioclase, albite, and potassium feldspars are all present in shale, and like clays, their relative abundance changes during burial through progressive disappearance of potassium feldspar and calcic plagioclase (Hower et al., 1976).

Quartz and amorphous silica varieties are found in all size fractions. They are derived from sources which are terrestrial (weathering, volcanism), biologic (sponges, diatoms), or are formed during diagenesis. All are subjected to mobilization by solution and deposition and

may radically change the hydrologic properties of a rock by filling pore space and/or making it brittle.

Carbonates are primarily found as calcite and aragonite of biogenic origin. Their tendency to mobilize is greater than that of silica and results in concentrations in the form of concentrations or pore space fillings. Typical shale contains less carbonates than silica.

Detrital mica is mainly altered muscovite and occurs in the form of flakes which can impart fissility to the rock.

In summary, the physical properties of shale depend mainly upon the abundance of clay minerals and the relative proportions of clay types. When kaolinite and illite predominate, rock properties are likely to remain fairly constant and predictable. When smectites and smectite-rich mixed layer clays are the most common, rock properties can be unpredictable and be subjected to changes by reaction with pore fluids. Other minerals that are present are less likely to have a widespread effect on shale properties.

3- ENVIRONMENTS OF DEPOSITION OF SHALE

Shale and related rocks are found in sedimentary units of both continental and marine origin. The accumulation of fine-grained sediment requires (a) an abundant source of

clay-size fragments generally derived from the chemical weathering of landmasses and (b) relative reduction in the proportion of coarser fractions either by sorting in a turbulent current (streams, surf, wind, etc.) or by sudden accumulation of clay-size fragments with no increase in the amount of deposited coarser fractions. Since such conditions can be realized in a multitude of ways, beds and lenses of shales can be expected in terrestrial environments (flood plains, lakes), near shorelines (lagoons, sheltered inlets), on the continental shelf (the "normal" setting of shale), or in abyssal plains (turbidites, clays, oozes). Shale is seldom found without other clastic sediments. When it predominates, stratigraphic units may be named after it: for example, Chinle Shale is the name of a Triassic formation of the Colorado Plateau which also contains sandstone and conglomerates.

Large accumulations of shale are mainly marine in origin. They are particularly thick in areas of high subsidence rates and moderate tectonic deformation such as miogeoclines and stable continental margins (trailing edges). Surprisingly, large accumulations of shale can also be found in terrestrial environments. One classic example is the Green River Formation (Middle Eocene) which contains, in addition to true shale, siltstones and carbonate rich Oil Shale.

4- DIAGENESIS OF SHALE

Shale undergoes profound changes between the time it settles as a soft sediment and until it acquires the appearance of a rock. This "curing" process or diagenesis is quite complex: water is expelled by compaction, new minerals form, grain-size changes, the composition of pore fluids is modified, and occasionally, pores are filled with silica or calcite. The following discussion deals mainly with the diagenetic effects which may affect the hydrologic properties of shale.

Compaction

Because deposition of shaly material takes place slowly and in a quiescent environment, the settled sediment is initially very rich in fluid--up to 90% (Smith, 1971). The platy habit of the clay results in a finely layered structure. This initial state reduces vertical permeabilities and influences the diagenetic changes which follow. As pressure of overlying sediments increases, fluids are generally expelled, pores collapse, and the rock becomes dense and less permeable. The decrease in permeability may temporarily prevent fluids from escaping; thus the pore pressure rises while porosity and density remain nearly constant. This somewhat "anomalous" behavior is often observed in thick shale layers which have undergone rapid

burial. Ultimately, the sequence of events ends with the expulsion of fluids and the formation of a compacted sedimentary rock.

Mineralogic Changes

Under the conditions of pressure and temperature which are likely to prevail in a depositional basin (less than 10 km deep, less than 200° C) the mineralogic changes affect mainly smectites and illite/smectite mixed layer clays. According to Powers (1967) smectite undergoes dehydration and begins to change to illite at a depth of 2,000m, and the reaction is complete at about 3,500 m. More recently, this transitional process was thoroughly investigated by Hower et al. (1976), Aronson and Hower (1976), and Yeh and Savin (1977). Results show that between 1,400 m and 3,800 m and at temperatures between 44 and 100°C shales from the Gulf Coast area exhibit a progressive enrichment of illite (from 20 to 80%) in the illite/smectite mixed layer clays. No further change occurs until about 7,500 m (and at about 200°C) where both, the remaining smectite and the illite disappear, and shales evolve into a low-grade greenschist assemblage of dioctahedral mica (muscovite), chlorite, albite, and quartz. The initial change follows the scheme:

and is not reversible. The potassium and aluminium are supplied by potassium feldspar, calcic plagioclase, and kaolinite, which show a conspicuous disappearance at depth. The reaction is further complicated by a loss of iron and magnesium.

Diagenetic changes have a tremendous impact on the hydrologic properties of shale. Changes in the smectite composition lower the variability in the plasticity, ion exchange characteristics, hydration-dehydration, semi-permeable behavior, etc. Water release, increased compaction, silica release and silicification may be equally important in some cases (Towe, 1962). The extreme conditions which are needed to eliminate completely the mixed layer clays are not common occurrences except perhaps in deeply buried, hence often oldest, shale, such as the argillites of the Precambrian Belt Series of Montana and Idaho (Maxwell and Hower, 1967).

There is compelling evidence that a relationship, perhaps unrelated to burial, exists between clay mineralogy and the age of the shale. Kaolinite and smectite-rich mixed layer clays are more common in Cenozoic shale whereas chlorite and illite predominate in pre-Mesozoic clays. This change may reflect (1) a variation in the source material, (2) deeper burial or (3) a dependence on the rate

of reaction for diagenetic changes. The two latter possibilities cannot be easily distinguished, but Hower et al. (1976) have concluded that burial metamorphism is at least partly responsible. They found that recent clays (which underwent shallow burial) contain 30% illite, that Cenozoic and Mesozoic clays (buried to variable depths) contain between 30 and 65% of randomly stratified illite, and that pre-Mesozoic clays contain 65% illite with ordered interstratification. Similar age-related changes are found with other minerals. Among them are the progressive disappearance of carbonates, calcic plagioclase, and potassium feldspars and the progressive increase in quartz and albite.

Although these diagenetic reactions are able to alter drastically the hydrologic properties of shale, such modifications are unlikely to be felt within the expected life span of a waste repository. A more important practical aspect of shale diagenesis is that, for repository purposes, rocks with less smectite in the clay fraction will be less reactive with ground water. For that reason older rocks are likely to have more predictable hydrologic properties.

Changes in Pore Fluids

The composition of pore fluids in the early stages of burial is the same as that of the environment of deposition:

fresh water or lake brine for terrestrial sediments and sea water for marine deposits. Later, interactions with the surrounding rocks occur: the transformation of smectite into illite decreases the K/Na ratio, and E_h and pH undergo changes which affect the concentrations of SO_3^{2-} , H_2S , NH_4^+ , and NO_3^- . As the ion exchange sites on the clays become saturated, the shale acts as a semi-permeable membrane. The resultant osmotic pressures have been observed to modify predicted patterns of fluid flow by their effect on hydraulic gradients (Berry, 1959).

Other Changes

A common diagenetic change is the growth of larger grains at the expense of smaller fragments of the same materials. In shale the process affects more often quartz and carbonates than clays and contributes to the filling of pores and the disappearance of plasticity. Locally, it may result in a dense massive rock in which later deformations may induce fracture permeabilities much higher than those ordinarily found in shale.

To sum up, during diagenesis the physical, chemical, and hydrologic properties of shale can be modified by predictable regional factors--depth of burial, age, initial composition, etc.--or by local conditions which are more difficult to evaluate--osmosis, loss of plasticity, etc.

5- POST DIAGENETIC CHANGES

Two changes which affect the hydrologic properties of shale after diagenesis are late fracturing and modification of the pore space in response to the circulation of ground fluids. The first effect is likely to be significant in areas of active faulting, particularly over a time span of 100,000 years. The second may be important in areas of active volcanism where hot fluids are potent agents of solution and deposition.

6- MAJOR SHALE OCCURRENCES

IN THE UNITED STATES

Shale appears on nearly all geologic maps of the United States. Many units are in the form of thin interbeds in clastic sequences and, as such, offer limited potential for repository sites. Others, more suitable for such use, occur in massive beds up to a thousand meters thick and have a wide areal extent.

The thickest and widest shale units are Cenozoic and Mesozoic in age and are found mainly west of the Mississippi Valley. Believed to be the source of many petroleum deposits, they have received more attention than the older shale. A few widespread Paleozoic shales are found, mainly east of the Rocky Mountains, and occasionally,

thick Precambrian shales have been described in scattered parts of the continent. The following major shale units are listed in order of increasing age:

Tertiary Shale

Shale of marine origin is found in the thick clastic wedges of California (Great Valley, Coast and Transverse ranges) and the Gulf Coast. Its age ranges from Pliocene to Miocene in the Coast Range and to Eocene elsewhere. Shale of continental origin reaches considerable thickness in the northern Colorado Plateau (Green River Basin of Eocene age).

Cretaceous Shale

Shale of Cretaceous age occurs in several areas. Its greatest extent is a vast blanket spread from the Colorado Plateau to the edge of the Appalachians and from the Canadian Rockies to the Gulf Coast. This broad unit has received various names: it is best known as the Pierre Shale in the northern Great Plains and has been correlated elsewhere with such units as the Adaville, Mentor, Benton, etc. Also, the thick Mancos Shale from the Mesa Verde Wedge is partially time-equivalent to the Pierre Shale. Cretaceous shale is also found along the Atlantic coast (Middendorf Shale) and in the Great Valley sequence of California.

Jurassic and Triassic Shale

In contrast with previous groups, Jurassic and Triassic shale is rather uncommon. Exception is the continental shale in the Colorado Plateau (Upper Jurassic Morrison Formation) and along the East Coast (Brunswick Shale in Triassic Basins).

Paleozoic and Precambrian Shale

A particularly persistent shale unit occupies the Upper Paleozoic section between the Rocky Mountains and the East Coast. It is best known as the Chattanooga Shale with other names being approximate equivalents: Cherokee, Stanley, Hamilton, etc., but it must be pointed out that this unit does not have the same age everywhere (Clark and Stearns, 1968). Beyond the limits of the Chattanooga Shale, a somewhat similar unit is found in the Great Basin (eastern Nevada and western Utah). It is the Eleana Formation (Devonian-Mississippian) which is part of a thick flysch sequence in the Antler Trough (Poole and Sandberg, 1977). Finally, a few instances of large shale units have been reported in the Upper Precambrian, for example, the Terrigenous Detrital sequence which occupies the same general area as the Elena Formation in the Great Basin and the Nonesuch Formation in the Northern Appalachians. Within the context of the data obtained

during the bibliographic search the shale-rich formations which are most favorable for use as waste repositories are those of Cenozoic age along the West and Gulf coast regions, those of Mesozoic age in the central portion of the country, and those of Triassic and Paleozoic age in the eastern half of the United States. These units are covered in the hydrologic part of this report. Formations which could be favorable but for which data were not available are listed in the Stratigraphic Tables.

THE HYDROLOGIC PROPERTIES OF SHALE

The preceding section provides a qualitative description of the factors which control the hydrologic properties of shale. This section discusses the quantitative aspects of the hydrologic parameters and their mathematical relationships. This review also will show areas of knowledge where further research is critically needed.

1- BRIEF REVIEW OF IMPORTANT PARAMETERS

This review will be limited to the rock properties which are discussed in this report or listed in the hydrologic tables.

Porosity

Percent porosity, ϕ , is the ratio of void space V_v , to the bulk volume of the rock ($V_{\text{solid}} + V_v$). Where:

$$\phi = \frac{V_v \times 100}{V_{\text{solid}} + V_v}$$

In hydrology there is some advantage in distinguishing absolute porosity (total void porosity) from effective porosity (connected-void porosity). Only the latter is related to rock permeability, but in the case of shale the

distinction becomes unclear by the fact that pore connection varies with the amount of adsorbed fluid which may swell the clay particles. When reservoir properties have to be estimated, it is also important to distinguish primary porosity which is widespread and more easy to predict from secondary porosity, fracture or solution, porosity which is controlled by local and more variable factors.

Permeability

Permeability is a measure of the ability of a fluid to flow through rocks under a pressure gradient. It is an intrinsic rock property which, in the CGS system, is expressed either in darcys or in cm^2 , with the equivalence:

$$1 \text{ darcy} = 9.87 \times 10^{-9} \text{ cm}^2$$

A related parameter is hydraulic conductivity (K^*) which appears in Darcy's law as:

$$K^* = QH/A ,$$

where Q is the fluid discharge, A the area through which the fluid moves, and H is the hydraulic gradient (change of elevation or pressure). The hydraulic conductivity and permeability k are related by the expression:

$$K^* = \frac{kg}{\nu}$$

where v is the kinematic viscosity (in stokes) and g the gravity acceleration. In the metric system hydraulic conductivity is expressed with the dimensions of velocity: cm/sec, m/yr etc. The following are convenient expressions of K^* :

$$1 \text{ cm/sec} \approx 1.03 \times 10^3 \text{ darcys (for water at } 20^\circ\text{C)}$$

$$1 \text{ m/yr} \approx 3.27 \times 10^{-3} \text{ darcys}$$

$$1 \text{ darcy} \approx 306 \text{ m/yr.}$$

It must be noted that, due to the kinematic viscosity factor, the hydraulic conductivity varies with temperature. Thus, at 100°C ,

$$1 \text{ cm/sec} \approx 3.44 \times 10^3 \text{ darcys.}$$

Permeability and hydraulic conductivity are directional properties which can vary substantially. The scant data available (see, for example, Table Region I, Core-Hole 65/2W-24C7, Santa Clara Valley) suggest that variations can reach two orders of magnitude. It is important to remember that most permeabilities are measured along the bedding ("horizontally") and that in shale such values are the highest. In the exceptional case where "vertical" permeabilities are greater, there is evidence of fracturing or solution. When permeabilities are isotropic there is indication of a uniform equigranular medium which is more

likely to be found in silstone than in shale or mudstone.

Other Parameters

Diffusivity. Hydraulic diffusivity α is defined by the expression:

$$\alpha = \frac{K^* D}{S}$$

where K^* is the hydraulic conductivity. For an unconfined system, D is the average saturation thickness and S represents the specific yield. For a confined system, D is the thickness of the producing formation and S is the storage coefficient. Diffusivity enters in the calculation of movements of transient volumes or "slugs" of fluid.

Rock density is a property which is obtained routinely from well logs. It can be used as a rough indicator of porosity provided that the grain density can be assumed to be constant (generally around 2.65). In that case, the porosity ϕ should be:

$$\phi = \frac{2.65 - d}{2.65} \times 100$$

where d is the dry density of the sample. This figure, however, does not take into account the fact that water

adsorption can swell clays from the solid fraction and reduce the grain density. In practice measured porosities of shale can be nearly 50% less than those predicted by the equation.

Well logging parameters. Among the data which are obtained from well logs are the electrical resistivity and self potential from which porosities and permeabilities can be estimated in situ. Another useful parameter is the acoustic transit time obtained from sonic logs. Magara (1973) has derived the following empirical relationship between acoustic transit time Δt and porosity ϕ :

$$\phi = 0.00472 \Delta t_{\text{shale}} - 0.362$$

The transit time is measured in microsec/ft. The equation holds true for Cretaceous and Tertiary shale of North America.

2- MATHEMATICAL RELATIONSHIPS

Permeability measurements are difficult to obtain in a laboratory because core drilling often induces cracks or fissures. Typically the values obtained are too high and erratic. In situ estimates of shale permeability by producing fluid from a drill hole are also difficult because shale normally produces no fluid. For this reason

many attempts have been made to determine permeability from well log data. Some of the most useful expressions are described below.

Permeability-porosity relationships appeared in the literature long ago. The most familiar was derived by Kozeny in 1927 (in Magara, 1973) and has the form:

$$k = \frac{P}{B A_g} \times \frac{\phi^3}{(1-\phi)^2}$$

where A_g is the grain area per unit volume, P and B are parameters related, respectively, to the pore shape and to the "tortuosity" of the pore, and k and ϕ are, respectively, permeability and porosity. In practice these empirical parameters are incorporated in simplified equations. Ryder (in Levorsen, 1967) suggested:

$$k = \frac{2 \times 10^7}{A_g^2} \times \frac{\phi^3}{(1-\phi)^3};$$

Vasquez (in Smith, 1971) proposed:

$$k = b \frac{\phi^a}{(1-\phi)^c}$$

where a , b , and c are derived empirically for particular rock types. He used $a = 8$ and $c = 0$ for shale, figures also used by Smith (1971, 1973), and Archie (in Magara,

1973) used a value of 5.5 for a and 0 for c . A different and, perhaps, more reliable procedure was used by Magara (1973) who, using porosities from acoustic logs in incompletely compacted shales and fluid pressure gradients, was able to predict quite accurately the permeabilities of Cretaceous shales of central Canada (equivalents of the Pierre Shale).

The various predictions are shown in Figure 1 where the extent of their reliability can be easily tested. It is readily seen that Magara's data derived from well logs plot more accurately than laboratory derived determinations. However, the lack of data below porosities of 10% makes extrapolations questionable in that direction. A word of caution is needed to remind that the described relationships do not include fracture permeability. Studies by Webster et al. (1970) on metamorphic rocks seem to suggest that substantial conductivity (5×10^{-7} cm/s) can be associated with exceedingly small porosities (0.01%). Similar figures may apply perhaps to the non-porous Paleozoic shale listed in the tables below.

Porosity-depth relationships are a necessary supplement to the calculations above. The simplest models take the exponential form suggested by Rubey and Hubbard (1959):

Figure 1:

Permeability/porosity relationships calculated for various mathematical models: 1-Archie (1950); 2-Magara (1973); 3-Kozeny (1927); 4-Smith (1971). Circles: Laboratory-measured porosities and permeabilities of shale and siltstone. Crosses, similar data for clays; K: kaolinite; S = smectite. Values calculated from log-derived data by Magara fall within the cross-hatched area.

$$\phi = \phi_0 e^{-cz}$$

where z is depth, ϕ_0 a reference, surface porosity, and c an empirical constant. For Cretaceous and Tertiary shale of North America and Japan Magara (1973) derived the expression:

$$\phi = 0.6 e^{-0.0000193 z \text{ (cm)}} .$$

Athy (in Smith, 1971) used the following equation for shale of north-central Oklahoma and Kansas:

$$\phi = 0.48 e^{-0.0014 z \text{ (m)}}$$

Such equations give values of so-called "normal porosity" characteristic of rocks where hydrostatic pore pressures prevail. It is against these references that pore overpressures due to rapid burial can be evaluated.

The previous discussions have been concerned mainly with primary porosity and bear little relationship to fracturing. Although Snow (1968) found that fracture porosity of most rocks decreases exponentially with depth (an order of magnitude every 61 m), du Rouchet (1978) has shown that open fractures can develop spontaneously in shale subjected to high pore pressures at depths between 1,000 and 2,000 m.

Theoretical models give permeability relationships which are seemingly more reliable than those derived from laboratory measurements only when porosities exceed 10% and permeabilities higher than 10^{-8} darcys (3.06 m/yr). Below these levels the calculated permeability figures could be in error by several orders of magnitude.

3- LITHOLOGIC PARAMETERS

Kozeny's equation contains an explicit statement of most lithologic factors likely to affect shale permeability (with the exception of grain mineralogy); the specific surface is related to grain size, the pore shape is related to the sphericity and roundness of grains, and the tortuosity is related to sorting (although such a statement is an obvious oversimplification). In the case of shale the relationship between porosity and permeability is complicated further by the fact that clay minerals have widely different surface properties. A look at Figure 1 shows that laboratory-measured permeabilities of kaolinite are generally higher than corresponding values for smectite. According to Mielenz and King (1955) both clays are found in the same size fraction, and since both have a similar platy habit, it is likely that the differences must be accounted for by the high adsorption characteristics of smectites. Harman and Fraulini (1940) have shown that the

permeability of kaolinite decreases by a factor of 3.5 when its specific surface is increased from 30 m^2 to 240 m^2 . In the absence of other data one might speculate that similar changes could exist for other clay minerals as well.

4- DIAGENETIC AND POST DIAGENETIC CHANGES

Compaction

The effect of compaction on the hydrologic properties of shale has been well investigated (Smith, 1971, 1973; Magara, 1973). Because of the low permeabilities of clays, rapid burial of clay-rich sediments may result in a build-up of fluid pressure and lead to abnormal porosity/depth relationships. Using similar approaches, Smith and Magara showed that these "abnormally" high pore pressures can persist for tens of millions of years, a fact also observed by Magara in the Upper Cretaceous shale of Canada. Smith (1971) has presented tables listing calculated variations in porosity, permeability, pressure, water velocity, etc. These calculated figures suggest that during compaction, permeability increases in general (and up to tenfold) while porosity decreases. It should be reminded, however, that Smith's assumptions about initial porosity/permeability relationships disagree with the seemingly more accurate

estimates of Magara (1973). There seems to be a consensus that compaction overpressures are unlikely to extend into the Paleozoic strata.

Mineralogic Changes

General knowledge of the adsorbing properties of clays suggests that the illitization of smectites is likely to be accompanied with important changes in hydrologic properties shale. For the present, however, numerical data is scant. In a series of experiments, Magara (1973) has shown that pore overpressure was not related to mineralogic changes at least to depths of 700 m. Both Powers (1967) and Hower et al. (1976) agree that the change of smectite to illite is accompanied with dehydration, but such changes should not operate at depths of less than 1250 m (observed by Hower et al., 1976, in Gulf Coast shale).

Reactions with Pore Fluids

Permeability of shale is likely to be affected during reaction with pore fluids, but precise data is once again scant. Samuels (1950) has shown that charges and nature of dissolved ions affect permeabilities (the higher the charge, the greater the permeability). Smectites are more affected than kaolinite (Fig. 2) with permeability ratios (Al/Na) being, respectively, 0 and 3.5. It is important to note that, although permeabilities decrease with pressure,

Figure 2: Effect of ion adsorption upon the permeability of two clay minerals: smectite (montmorillonite) and kaolinite. (From Samuels, 1950). In all cases clays are saturated with the particular cations.

their ratios remain seemingly constant. Presumably, illite would have a behavior somewhere between smectite and illite, and a reasonable guess would be that the ionic substitution effect would be reduced during the illitization of smectite-rich sediments. Another guess would be that permeability of shale can increase if different ions are introduced by ground water movements.

Cementation

Since the illitization of clay is a possible source of soluble silica (Towe, 1962), drastic drops in porosity and permeability can be expected during burial. If such changes were to take place, however, they would produce anomalous porosity/permeability relationships which may be detectable on curves such as those of Figure 1. Obviously, a silicified shale could also yield rocks of high fracture permeability, but such instances would be very difficult to predict.

CONCLUSIONS

The preceding discussions are perhaps more revealing of the great gaps in our knowledge of relationships between lithology and hydrologic properties. It is true that much work remains to be done before accurate predictions for long periods of time become possible, but a few important facts have been established: 1--within a formation of

particular age reliable correlations between permeability and porosity can be established (this method has been used for estimating some of the figures shown in the tables below): 2--Mineral composition must be known in order to predict possible long-term effects of ion exchange on shale; and 3--The chemical composition of pore fluids must be determined in order to predict possible effect of fluid waste leakage on enclosing rocks. On the other hand, more work is needed to be able to predict permeabilities below 10^{-8} darcys, and to determine the effect of burial on the hydrologic properties of clays. The tables which follow show that the hydrologic data for shale is rapidly growing and provide a bright outlook for future research.

THE HYDROLOGIC CHARACTERISTICS OF SHALE
IN THE UNITED STATES

ORGANIZATION OF THE DATA

The following lists of hydrologic properties of shales are divided among six geologic areas (Fig. 3). Each list is preceded by a brief description of the geology of the region and a stratigraphic table designed to show the position of the shales with respect to other geologic units.

For each region permeabilities, porosities, and densities are presented first, and the other parameters for which there are less data are listed in a separate "additional data" sheet. Bibliographic references of the hydrologic data are listed in alphabetical order with each section to make them more readily available for further search.

In general, permeability values were changed into water conductivities at 15°C using the equivalence:*

$$1 \text{ darcy} = 8.54 \times 10^{-4} \text{ cm/s} .$$

---

*S. Davis and R. DeWiest, 1966, Hydrogeology, p. 165, John Wiley & Sons, New York.

Figure 3. Location of areas containing shales which are discussed in the table of hydrologic properties.

REGION 1: PACIFIC COAST-

COAST VALLEY-GREAT BASIN

The western edge of the American continent has been at the forefront of converging plate activity at least since Mid-Paleozoic times and lasted intermittently until Late Cenozoic when subduction was replaced by a combination of transcurrent regime along the San Andreas Fault System and of tensional deformation in the Great Basin (Atwater, 1970). As plates were consumed under North America, shale-rich sediments were laid down in a series of linear basins more or less parallel to the present Pacific shorelines. The oldest zone of deposition developed during the Paleozoic in an area presently located in eastern Nevada and western Utah; the younger ones appeared in the Great Valley of California and in the Coastal and Transverse Ranges. The following shales are associated with these zones.

-The Great Basin shales belong to the Terrigenous Detrital Sequence (Stewart and Suczek, 1977), and the Eleana formation respectively, of Eocambrian-Cambrian and Devonian Mississippian ages. Stewart and Suczek (1977) believe that their Terrigenous Detrital sequence evolved during the early stages of opening of ancestral Pacific Ocean. Its location is shown in Figure 4.

Figure 4: Map showing the location of the Cambrian Terrigenous Sequence in the Great Basin. (From Stewart and Suczek; 1977). The stippled area shows the zone where the thickness of the sequence exceeds 300 m.

The Eleana Formation represents, according to Poole and Sandberg (1977), a forearc assemblage of the Antler geosyncline. Figure 5 shows its general location and thickness. Both shales of the Great Basin are included into the stratigraphic Table 4-1-a.

-The great Valley shales developed within a Mesozoic, and perhaps Tertiary, forearc basin which persisted nearly unchanged until present. During that time alternations of shale and sandstone were accumulated to thicknesses which exceed locally 10,000 meters mainly as Cretaceous, flysch-type, Great Valley sequence. The Panoche Formation is an example of a predominately shaly unit which locally reaches thicknesses of 6,700 m. The bibliographic search which was undertaken as part of this report did not include parameter values for this formation. Further search would be useful.

Cenozoic shale of the Great Valley is much thinner (less than 1,000 m) but, being associated with oil and gas fields, the rock has undergone more scrutiny. The many names of the shale formations of that group (Eocene to Pliocene) are shown in Table 4-1-b.

Coastal shale is Miocene and Pliocene in age and represents western extensions of similar units in the Great Valley.

Figure 5: Map showing the location of the Eleana Formation Facies (dotted area) within the Upper Devonian-Mississippian of the Great Basin (after Poole and Sandberg, 1977). Isopachs are labelled in 100 meters.

It is associated with hydrocarbon deposits. Examples of the structural style characterizing Great Valley and Coastal Range are given in Figures 6 and 7. Detailed stratigraphy is shown in Table 4-1-3.

Figure 6: Generalized section across the San Joaquin Valley. (From Eardley, 1962)

Figure 7: Generalized section across the Sacramento Valley. Designed to show the thickness of Mesozoic sediments after D.O. Emerson and E.I. Rich, 1966, in Bull. 190, Calif. Div. of Mines and Geol., San Francisco, p. 476.

TABLE 4-1-a SUMMARY OF PALEOZOIC ROCKS IN THE GREAT BASIN (EASTERN NEVADA, WESTERN UTAH)
[From Stewart and Suczek, 1977]

NOTE: Shales described in the hydrologic tables are preceded by *.

Age		Stratigraphic Unit	Thickness (M)	Description
PERMIAN		Antler Sequence	1,500	Miogeosynclinal limestones, dolomites, and minor mudstone
PENNSYLVANIAN		Tippipah Limestone	400 (approx.)	Massive limestone
DEVONIAN	Upper	Eleana Formation	3,000-1,500	Shales, sandstones, mudstones, and minor limestones of the Antler Flysch Trough
				-----Unconformity-----
	Middle	Nevada Formation	1,450-450	Silty dolomite
				-----Unconformity-----
	Lower	Spotted Range Dolomite	500-50	Dolomite, dolomitic limestone, with minor chert beds
SILURIAN		Upper		
ORDOVICIAN		Lower		
CAMBRIAN		Ely Springs Dolomite	360-40	Massive crystalline dolomite
				-----Unconformity-----
	Upper	Eureka Quartzite	1,000 (approx.)	Massive quartzite
	Middle	Antelope Limestone	1,000 (approx.)	Limestone with a few interbeds of siltstone
UPPERMOST PRECAMBRIAN		Lower	* Terrigenous Detrital sequence	Siltstone, carbonate rich siltstones, and fine grained quartzite

TABLE 4-1-b SUMMARY OF ROCK UNITS IN THE SAN JOAQUIN VALLEY AREA, CALIFORNIA
[From Kirby (1943), Hackel (1966), and Maher et al. (1966)]

NOTE: Shales described in the hydrologic tables are preceded by *.

Age	Stratigraphic Unit	Thickness (M)	Description
RECENT	Alluvium	0-45	Poorly sorted, unconsolidated silts, clays, and sands and pebbles
PLEISTOCENE	Tulare Formation	0-915	Non marine: Contains Corcoran Clay member, interbedded non-marine mudstones and pebbly sands
PLIOCENE	* San Joaquin Formation	0-549	Shale and interbedded clayey siltstone and silty sandstone
	Middle * ETCHEGOIN FORMATION		
	Carmen Sandstone member	394	Interbedded grayish-green siltstone and feldspathic glauconitic fine to medium grained sandstone
	Lower Tupman Shale member	406	Olive gray silty shale
MIOCENE	Upper * Reef Ridge shale	56-176	Soft blue clay shale, minor layers of sandy shale
	Middle * MONTEREY SHALE		Unconformity
	Elk Hills shale	549-1000	Gray siliceous shale, siltstone, and minor claystone
	* McDonald shale	95	Massive brown silty shale
	Gould and Devil-water shale member	59-235	Siliceous shale
	Lower * Temblor Formation	457	Contains Media shale member, alternating sandstone and shale sequence
			Unconformity
OLIGOCENE	Wagonwheel Formation	0-152	Argillaceous sandy shale interbedded with sandy beds

MARINE

Table 4-1-b (continued)

Age	Stratigraphic Unit	Thickness (M)		Description	
EOCENE	* Kreyenhagen Formation	274	Marine	Fissile shales and fine- to coarse-grained arkosic sandstones	
	Lobo Formation			Shales, sandy shales, sandstones	
PALEOCENE					
CRETACEOUS	Upper	CHICO SERIES	Miogeoclinal		
		Moreno Formation		915	Interbedded organic shale and fine-grained sandstone
		Panoche Formation		6,708	Predominantly shale with sandstone and conglomerate
	Lower	Shasta Series		6,098	Mudstone, siltstone, graywacke, conglomerate, and minor limestone
JURASSIC		Knoxville Formation	Eugeoclinal Facies	Black hackly fracturing shales or mudstones; massive lenticular conglomerates	
		Franciscan		>15,000	Graywacke, dark shale, volcanics, chert, limestones, metamorphics
				-----Unconformity-----	
PRE-JURASSIC & PALEOZOIC					

TABLE 4-1-c SUMMARY OF ROCK UNITS IN THE CALIFORNIA COAST RANGES
[From Page (1966), Cummings et al. (1962) and Kirby (1943)]

NOTE: Shales described in the hydrologic tables are preceded by *.

Age	Stratigraphic Unit	Thickness (M)	Description
PLEISTOCENE	Terrace Deposits	12	Interbedded coarse sand and gravels.
PLIO- PLEISTOCENE	* Santa Clara Formation	549	Poorly consolidated, interbedded conglomerates, sandstone and mudstone
PLIOCENE AND MIO-PLIOCENE	Purisima Formation	1,723	Sandstone, mudstone, siliceous mudstone and porcellanite, volcanic sandstones, diatomite, vitritic tuffs
MIOCENE	* Monterey Formation	2,744	Light-colored, diatomaceous and siliceous shale and sandstones
	Mindego Formation	610-1,220	Complex interstratified basaltic volcanic rocks, mudstone, sandstone, and carbonates
OLIGOCENE	Vaqueros Sandstone	732-1,372	Fine-to-medium-grained arkosic arenite with interbedded shale and mudstone
	San Lorenzo Formation	396-823	Mudstone and shale
-----Unconformity-----			
EOCENE	Butano Sandstone		Arkosic sandstone, including turbidite, with mudstone interbeds
PALEOCENE	Logatelli Formation	76-244	Dark gray, massive siltstone

TABLE 4-1-c (Continued)

Age		Stratigraphic Unit	Thickness (M)	Description
CRETACEOUS	Upper	GREAT VALLEY SEQUENCE		
		Forbes Formation	640	Mudstone, interbedded siltstone and sandstone
		Guinda Formation	335	Arkosic sandstone (turbidite)
		Funks Formation	457	Mudstone, minor sandstone
		Sites Formation	762	Arkosic sandstone; mudstone and siltstone
		Yolo Formation	945	Mudstone, minor sandstone
		Venado Formation	915	Arkosic Sandstone (turbidite); mudstone; local conglomerate
	Lower	Fiske Creek Formation	1,220	Mudstone; minor interbedded siltstone; sandstone
		Brophy Canyon Formation	457	Sandstone, mudstone, local conglomerate
		Davis Canyon Formation	1,951	Mudstone and feldspathic sandstone (turbidite); mudstone.
		Little Valley Formation	1,372	Mudstone and minor feldspathic sandstone (turbidite)
		Crack Canyon Formation	1,098	Mudstone, minor arkose, conglomerate lenses
JURASSIC	Upper	Knoxville Formation	>2,165	Mudstone, shale, graywacke, conglomerate lenses, basalt breccias and flows, detrital serpentine

TABLE 4-1-c (Continued)

Age	Stratigraphic Unit	Thickness (M)	Description
JURASSIC	Franciscan Formation Core	>15,000	Graywackes, shales, volcanics (pillow lavas), chert, limestone, metamorphics
	GRANITIC-METAMORPHIC CORE	Dual-Core Complex	
CRETACEOUS	Granitic Plutons		Quartz diorite, granodiorite, adamellite, 69-110 m.y.
PALEOZOIC (?)	Sur Series		Gneisses, schists, quartzites, marbles and granulites; metamorphic miogeoclinal equivalents

Hydrologic Data

Section I

PACIFIC COAST, GREAT VALLEY AND GREYH VASIN

Geological Setting	Age	Locality	Depth (ft)	Number of Samples	Porosity Avg. Max. Min.	Hydraulic Conductivity		Ref.	Determination Method	Notes
						Avg.	Max. Min.			
Silt & Clays	Recent	Santa Barbara basin off Southern California	1	No available data	79		6x10 ⁻¹²	2	From graph (p. 755)	a
			2		77		3.9x10 ⁻¹²			
			3		75		1.7x10 ⁻¹²			
			4		74		7.7x10 ⁻¹³			
			5		73		6.0x10 ⁻¹³			
Core-hole 75/1E-16C6 Clayey-Silt Clayey-Silt Clayey-Silt Clayey-Silt Silty-Clay	Recent-Pliocene	Santa Clara Valley, California	70.1	No available data	42.1		2.8x10 ⁻⁸	4	Porosity: (d) dry unit specific weight (s) measured, then porosity, then calculated from equation $\epsilon = \frac{w}{G} \frac{d}{1000}$	b
			70.7		40.9		9.4x10 ⁻⁹ (ii)	4		
			84.0		41.8		3.3x10 ⁻⁷ (v) 1.9x10 ⁻⁷ (ii)	4		
			101.9		40.7		9.4x10 ⁻⁹ (ii)	4		
			122.4		43.0		1.4x10 ⁻⁸ (v) 4.7x10 ⁻⁸ (ii)	4	Permeability: (see below)	

^a Analysis of 100 cores.

^b Bay sediments and Santa Clara formation (boundary not located on cores). ii = horizontal hydraulic conductivity; v = vertical hydraulic conductivity.

REGION 1 (continued)

Geological Setting	Age	Locality	Depth (ft)	Number of Samples	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
					Avg.	Max.	Min.	Avg.	Max.	Min.			
[Core-Hole 75/IE-16C6]	Recent-Pliocene	Santa Clara Valley, California		No available data									
Clayey-Silt			247.5		40.9			4.7×10^{-7} (H)			4	Permeability: Measured using both a constant head permeameter for	
Clayey-Silt			277.0		34.8			9.4×10^{-9} (V) 1.4×10^{-8} (H)			4	samples with medium to high permeability and a variable head permeameter for samples with low permeability.	
Clayey-Silt			285.9		40.8			4.7×10^{-9} (V) 9.4×10^{-8} (H)			4		
Core-Hole 65/2W-24C7	Recent to Pliocene	Santa Clara Valley, California		No available data							4	(Same as above)	b
Clayey-Silt			15.3		40.8			No available data					
Clayey-Silt			21.9		39.3			4.8×10^{-5} (V) 4.8×10^{-5} (H)					
Silty-Clay			27.6		44.7			2.4×10^{-5} (V) 3.8×10^{-5} (H)					
Silty-Clay			43.1		40.5			1.9×10^{-5} (V) 3.3×10^{-5} (H)					

^b See core hole 75/IE-16C6

REGION 1 (continued)

Geological Setting	Age	Locality	Depth (ft)	Number of Samples	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
					Avg.	Max.	Min.	Avg.	Max.	Min.			
(Core-Hole 65/2W-24C7)	Recent to Pliocene	Santa Clara Valley, California		No available data							4		
Silty-Clay			48.8		41.4			9.5×10^{-5} (V) 9.5×10^{-5} (II)					
Clayey-Silt			54.4		41.0			1.9×10^{-4} (V) 9.5×10^{-5} (II)					
Silty-Clay			58.4		36.8			2.8×10^{-8} (V) 3.3×10^{-8} (II)					
Silty-Clay			67.9		43.4			1.9×10^{-7} (V) 4.7×10^{-8} (II)					
Clayey-Silt			93.7		37.1			9.4×10^{-9} (V) 1.9×10^{-8} (II)					
Clayey-Silt			100.7		37.6			3.8×10^{-7} (V) 4.2×10^{-7} (II)					
Clayey-Silt			124.5		36.4			4.9×10^{-9} (V) 1.4×10^{-7} (II)					
Clayey-Silt			139.8		39.3			4.7×10^{-8} (V) 2.4×10^{-7} (II)					
Clayey-Silt			166.3		38.5			1.4×10^{-8} (II)					
Clayey-Silt			171.8		39.9			9.4×10^{-8} (V) 9.4×10^{-8} (II)					

REGION I (continued)

Geological Setting	Age	Locality	Depth (ft)	Number of Samples	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
					Avg.	Max.	Min.	Avg.	Max.	Min.			
[Core-Hole 65/2W-24C7]	Recent to Pliocene	Santa Clara Valley, California		No available data							4		
Silty-Clay			210.3		37.0			3.3×10^{-8} (V)	2.4×10^{-8} (II)				
Silty-Clay			227.2		44.9			2.4×10^{-8} (V)	4.7×10^{-8} (II)				
Clayey-Silt			247.6		37.4			1.9×10^{-8} (V)	4.7×10^{-8} (II)				
Silty-Clay			263.8		40.1			9.4×10^{-9} (V)	3.0×10^{-8} (II)				
Clayey-Silt			266.0		31.4			9.4×10^{-9} (II)					
Silty-Clay			274.5		39.4			1.9×10^{-7} (II)					
Clay			281.7		43.7			1.9×10^{-7} (V)	3.3×10^{-7} (II)				
<u>Core-Hole 24/26-36A2</u>	Upper Pliocene to Pliocene (?)	Tulare-Wasco Area, California		No available data							4	(Same as above)	c
Clayey-Silt			257.2		40.9			1.4×10^{-7} (V)					
Silt			259.9		46.0			2.8×10^{-7} (V)					

^c Marine strata.

55

REGION 1 (continued)

Geological Setting	Age	Locality	Depth (ft)	Number of Samples	Porosity	Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
						Av.	Max.	Min.			
Core-Hole 19/15-39H	Pleistocene to Upper Pliocene	Los Banos-Kettleman Hills Area, California		No available data					4	(Same as before)	d
Clayey-Silt			154.8		42.9		9.4×10^{-8} (V)				
Clayey-Silt			155.4		48.4		2.8×10^{-7} (V)				
							1.6×10^{-8} (H)				
Clayey-Silt			160.4		47.9		9.4×10^{-8} (V)				
							1.8×10^{-7} (H)				
Core-Hole 19/17-22H, 2	Pleistocene to Upper Pliocene	Los Banos-Kettleman Hills Area, California		No available data					4	(Same as before)	d
Clayey-Silt			237.5		42.9		1.9×10^{-8} (V)				
Clayey-Silt			247.1		43.4		2.4×10^{-7} (V)				
Etchegoin Formation	Pliocene	Naval Petroleum Reserve #1, Elk Hills, California							6	Self potential log and core analysis	e
Bullminella Silt Zone, Well 324-19R			1225-1236	14	20 32 24	10^{-2}	6.8×10^{-2}	0			
			1230-1436	60			(all wells = 0)				

^a See sample core held 65/2W-24C7

^d Torcoran Shale.

^e Olive-gray silty shale beds, makes up Tuleman Shale member.

REGION I (continued)

Geological Setting	Age	Locality	Depth (ft)	Number of Samples	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
					Av.	Max.	Min.	Av.	Max.	Min.			
<u>Reef Ridge Shale</u>	Middle to Late Miocene	Naval Petroleum Reserve #1, Elk Hills, California	1439-1482	13				(all wells = 0)			6	Self potential log and core analysis	f
<u>Monterey Shale and Stevens Oil Zone</u>	Middle to Late Miocene	Naval Petroleum Reserve #1, Elk Hills, California									6	(Same as above)	9
N-ZONE													
358-22R			2220-2221	4	17	20	15	1.1×10^{-2}	2.3×10^{-2}	4×10^{-3}			
378-22R			2095	2	14	14	14	3×10^{-4}		0			
N-ZONE													
342-3G			2139-2150	8	20	25	14	2.2×10^{-2}	7.3×10^{-2}	0			
362-3G			2125-2143		20	29	12	1.1×10^{-2}	3.6×10^{-2}	0			
382-3G			2140-2153	20	15	19	12	1×10^{-3}	6×10^{-3}	0			

^f Brown clayey and silty shale beds.

⁹ Brown to gray diatomaceous siltstones, and lesser amount of N-G, silty, partly siliceous shale, and very fine to medium grained silty sandstone.

REGION 1 (continued)

Geological Setting	Age	Locality	Depth (ft)	Number of Samples	Porosity			Hydraulic Conductivity (cm/g)			Ref.	Determination Method	Notes
					Avg.	Max.	Min.	Avg.	Max.	Min.			
(Montealegre Shale and Stevens Oil Zone)	Middle to Late Miocene	Naval Petroleum Reserve #1, Elk Hills, California									6		g
A-ZONE													
341-4G			1984-2044	9	16	20	11	6×10^{-4}	4×10^{-3}	0			h
382-4G			2055-2067	16	15	21	8	3×10^{-3}	1.1×10^{-2}	0			
370-22R			2099-2204	50	17	26	12	1.9×10^{-2}	3×10^{-1}	0			
322-25R			1647-1704	19	16	23	8	7×10^{-3}	1×10^{-2}	0			
312-26R			1962-1963	3	20	23	14	1.4×10^{-1}	3×10^{-1}	1×10^{-3}			
344-26R			1830-1876	10	19	26	13	5.2×10^{-1}	1.9×10^{-1}	0			
526-28R			1571-1576	5	23	25	18	2×10^{-3}	6×10^{-3}	0			
344-10S			2241-2200	14	14	21	9	1×10^{-3}	5×10^{-3}	0			
542-31S			1530-1537	5	23	30	7	2×10^{-3}	5×10^{-3}	0			
366-12S			1706-1757	33	14	23	10	1.4×10^{-2}	7.1×10^{-2}	0			

^gSee previous page.

^hBrown to gray diatomaceous, partly sandy dolomitic siltstone interbedded with brown to gray silty mostly siliceous shale, gray silty very fine grained sandstone in beds 1-4 feet thick, and some thin layers of dolomite.

REGION I (continued)

Geological Setting	Age	Locality	Depth (ft)	Number of Samples	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
					Avg.	Max.	Min.	Avg.	Max.	Min.			
Monterey Shale and Stevens Oil Zone)	Middle to Late Miocene	Naval Petroleum Reserve #1, Elk Hills, California									6		h
A-ZONE													
108-125			1866-1890	7	18	19	16	4×10^{-5}	2×10^{-1}	0			
386-335			2076-2086	13	18	23	10	8×10^{-3}	2.2×10^{-2}	0			
337-345			2020-2021	2	16	19	13	3.5×10^{-3}	1×10^{-3}	0			
344-345			2137-2152	17	17	20	13	3×10^{-3}	1.5×10^{-2}	0			
326-355			2027-2043	19	17	22	11	4.6×10^{-3}	6×10^{-3}	0			
344-355			2090-2095	8	17	26	13	5.9×10^{-2}	2.5×10^{-1}	6×10^{-3}			
384-355			2166-2172	7	19	21	16	1.2×10^{-2}	4.5×10^{-2}	0			
17-142			1513-1518	8	24	29	19	2×10^{-3}	1.1×10^{-2}	0			
B-ZONE													
142-2G			2218-2420	415	22	32	9	7.5×10^{-5}	7.9×10^{-4}	0			i
342-3G			2152-2326	413	23	33	8	1×10^{-4}	8.7×10^{-4}	0			

^hSee previous page.

ⁱInterbedded brown to gray diatomaceous siltstone, brown to gray silty mostly siliceous shale and very fine-grained silty sandstone.

REGION 1 (continued)

Geological Setting	Age	Locality	Depth (M)	Number of Samples	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
					Av.	Max.	Min.	Av.	Max.	Min.			
(Monterey Shale and Stevens Oil Zone)	Middle to Late Miocene	Naval Petroleum Reserve #1, Elk Hills, California									6		i
B-ZONE													
382-3G			2168-2346	402	22	29	12	1.8×10^{-4}	1.2×10^{-3}	0			
343-4G			2064-2221	247	22	29	14	9.8×10^{-5}	7.9×10^{-4}	0			
346-4G			2211-2334	121	17	26	6	3.6×10^{-5}	3×10^{-4}	0			
382-4G			2118-2284	155	22	30	11	9.8×10^{-5}	1.9×10^{-3}	0			
321-5G			1830-1940	178	22	29	13	1×10^{-4}	6.1×10^{-4}	0			
362-5G			1976-2063	145	23	29	14	6.5×10^{-5}	6.9×10^{-4}	0			
342-6G			2205-2206	2	15	16	14	3.4×10^{-6}	4.3×10^{-6}	2.6×10^{-6}			
342-6G			2236-2237	3	13	14	12	5.1×10^{-6}	1.1×10^{-5}	1.7×10^{-6}			
362-6G			2141-2145	3	19	21	18	9.4×10^{-6}	1.7×10^{-5}	8.6×10^{-7}			
322-23R			2709-2719	28	8	14	8	2.9×10^{-7}	0.6×10^{-7}	0			
388-23R			1876-1991	120	23	30	16	3.5×10^{-5}	5.5×10^{-4}	0			
322-25R			1711-1771	61	21	26	12	1.6×10^{-5}	1.8×10^{-4}	0			
335-25R			1641-1700	75	22	32	16	2.5×10^{-5}	1.8×10^{-4}	0			

i See previous page.

REGION I (continued)

Geological Setting	Age	Locality	Depth (M)	Number of Samples	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
					Av.	Max.	Min.	Av.	Max.	Min.			
(Monterey Shale and Stevens Oil Zone)	Middle to Late Miocene	Naval Petroleum Reserve #1, Elk Hills, California									6		
8-ZONE													
348-25R			1679-1767	60	23	31	14	3.0×10^{-5}	1.2×10^{-4}	0			
362-25R			1842-1909	70	22	30	11	1.4×10^{-5}	9×10^{-5}	0			
368-25R			1589-1685	6	21	26	17	5.8×10^{-5}	1.5×10^{-4}	8.6×10^{-6}			
382-26R			1687-1777	115	21	29	6	2.1×10^{-5}	5.4×10^{-4}	0			
382-26R			1813-1912	56	21	27	13	3.3×10^{-5}	2.6×10^{-4}	0			
526-28R			1634	1	20	20		1.2×10^{-5}	1.2×10^{-5}				
526-28R			1656	1	25	25		1.9×10^{-4}	1.9×10^{-4}				
342-34R			2482-2529	18	13	19	7	3.6×10^{-7}	2.6×10^{-6}	0			
362-36R			1668-1771	65	23	32	17	5.9×10^{-5}	4.5×10^{-4}	8.6×10^{-7}			
326-30S			1740-1830	63	24	31	14	1.4×10^{-5}	7.6×10^{-5}	0			
388-30S			1953-2025	4	17	20	14	1×10^{-5}	2.7×10^{-5}	2.6×10^{-6}			
322-31S			1588-1663	70	21	29	11	2.3×10^{-5}	1.1×10^{-4}	8.6×10^{-7}			
325-31S			1716-1769	50	22	29	17	1.1×10^{-4}	4.5×10^{-4}	0			

REGION I (continued)

Geological Setting	Age	Locality	Depth (ft)	Number of Samples	Porosity			Hydraulic Conductivity (cm/g)			Ref.	Determination Method	Notes
					Av.	Max.	Min.	Av.	Max.	Min.			
[Monterey Shale and Stevens Oil Zone]	Middle to Late Miocene	Naval Petroleum Reserve #1, Elk Hills, California									6		
B-ZONE													
366-31S			1661-1740	103	25	36	15	8.6×10^{-4}	9.7×10^{-4}	0			
383-31S			1644-1753	46	21	27	15	1.0×10^{-5}	6.2×10^{-5}	8.6×10^{-7}			
389-31S			1860-1993	79	21	28	11	3.5×10^{-5}	5.4×10^{-4}	0			
542-31S			1586-1628	33	29	35	15	9.7×10^{-5}	1.6×10^{-3}	0			
322-32S			1842-1917	33	18	23	10	1.1×10^{-5}	9.9×10^{-5}	0			
326-32S			1680-1752	119	23	30	14	4.9×10^{-5}	7.1×10^{-4}	0			
366-32S			1757-1877	183	17	29	8	6×10^{-5}	3.6×10^{-4}	0			
384-32S			1940-2069	168	21	29	5	2.6×10^{-5}	1.6×10^{-4}	0			
388-32S			1902-2005	193	22	29	12	4.6×10^{-5}	5.8×10^{-4}	0			
348-33S			2005-2122	212	22	29	9	1.2×10^{-4}	3.9×10^{-3}	0			
306-33S			2087-2230	274	21	28	10	6.1×10^{-5}	1.3×10^{-3}	0			
337-34S			2070-2071	1	15	15		5.1×10^{-6}	5.1×10^{-6}				
337-34S			2092-2198	271	22	29	15	1.4×10^{-4}	4.1×10^{-3}	0			

REGION I (continued)

Geological Setting	Age	Locality	Depth (ft)	Number of Samples	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
					Avg.	Max.	Min.	Avg.	Max.	Min.			
(Monterey Shale and Stevens Oil Zone)	Middle to Late Miocene	Naval Petroleum Reserve #1, Elk Hills, California									6		
B-ZONE													
344-345			2153-2226	130	10	25	13	5.1×10^{-6}	8.5×10^{-5}	0			
366-345			2036-2184	268	21	28	5	1×10^{-4}	7.3×10^{-4}	0			
384-345			2091-2220	242	18	24	12	2.9×10^{-5}	2.1×10^{-4}	0			
326-355			2046-2220	437	21	30	5	8.9×10^{-5}	9.8×10^{-4}	0			
344-355			2104-2271	218	21	28	11	1.2×10^{-4}	1.8×10^{-3}	8.6×10^{-7}			
366-355			2117-2297	398	21	30	6	5.1×10^{-5}	4.9×10^{-4}	0			
384-355			2212-2341	206	18	29	8	7.7×10^{-5}	6.7×10^{-4}	0			
324-317			2588-2747	179	19	24	5	9.4×10^{-6}	2.4×10^{-4}	0			
343-317			2637-2667	22	20	25	13	4.7×10^{-5}	4.8×10^{-4}	8.6×10^{-6}			
C-ZONE													
343-4G			2223-2250	27	18	22	14	4.3×10^{-6}	1.4×10^{-4}	0			j

j Gray, partly siliceous shale that includes some interbedded diatomaceous siltstone, some thin sandstone and dolomite layers.

REGION I (continued)

Geological Setting	Age	Locality	Depth (M)	Number of Samples	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
					Av.	Max.	Min.	Av.	Max.	Min.			
(Monterey Shale and Stevens Oil Zone)	Middle to Late Miocene	Naval Petroleum Reserve #1, Elk Hills, California									6		j
C-ZONE													
362-25R			1915-1922	12	21	26	18	3.6×10^{-5}	1×10^{-4}	1.7×10^{-6}			
382-26R			1708-1812	5	22	26	13	5.1×10^{-6}	1.6×10^{-5}	0			
386-26R			2046-2070	29	23	29	9	4.7×10^{-5}	1.7×10^{-4}	0			
322-36R			2019-2148	56	21	29	14	2.6×10^{-5}	1.6×10^{-4}	8.6×10^{-7}			
362-36R			1772-1785	10	16	24	11	5.1×10^{-6}	3.3×10^{-5}	0			
322-32S			1934	1	15		15	8.6×10^{-7}	8.6×10^{-7}				
366-32S			1912-1918	9	20	24	14	1×10^{-5}	2.8×10^{-5}	0			
326-35S			2222-2295	9	15	21	10	1.7×10^{-6}	6×10^{-6}	0			
324-31T			2750-2885	252	16	24	5	1.2×10^{-5}	4.7×10^{-4}	0			
D-ZONE													
368-25R			1794-1795	4	22	25	20	5.3×10^{-5}	1.4×10^{-4}	2.1×10^{-5}			k
366-32S			1962-1977	5	14	19	11	4.3×10^{-6}	8.6×10^{-6}	0			

^j See previous page.

^k Brown to gray diatomaceous siltstone, and brown to gray diatomaceous, silty shale.

REGION I (continued)

Geological Setting	Age	Locality	Depth (M)	Number of Samples	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
					Av.	Max.	Min.	Av.	Max.	Min.			
[Monterey Shale and Stevens Oil Zone]	Middle to Late Miocene	Naval Petroleum Reserve #1, Elk Hills, California									6		
UD-ZONE													
360-25R			1898-1934	53	21	31	15	3.3×10^{-5}	4.7×10^{-5}	0			1
302-26R			2003-2050	115	20	27	8	2.9×10^{-5}	3.5×10^{-5}	0			
E-ZONE													
343-4G			2486-2501	26	15	21	6	4.3×10^{-6}	1.5×10^{-5}	0			m
343-4G			2636-2692	78	18	25	11	1.7×10^{-6}	1.1×10^{-5}	0			n
343-4G			2736-2764	41	14	17	11	3.4×10^{-6}	9.4×10^{-6}	0			o
382-26R			2860-2071	33	18	26	12	0	0				
524-31S			1870-1973	5	18	22	16	4.3×10^{-6}	1.5×10^{-5}	0			

¹ Brown to dark silty shale, dark-gray siltstone, and in the lower half, some light gray silty sandstone.

^m Medium to dark gray siliceous and cherty shale abundant in lower part.

ⁿ Medium to dark gray, partly sandy siltstone abundant in middle and upper parts.

^o Several thin beds of fine-grained sandstone are present in upper part.

REGION 1 (continued)

Geological Setting	Age	Locality	Depth (ft)	Number of Samples	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
					Av.	Max.	Min.	Av.	Max.	Min.			
<u>McDonald Shale of Local Usage</u>	Miocene	Naval Petroleum Reserve #1, Elk Hills, California									6		P
343-4G			2085-2927	98	18	24	12	8.6×10^{-7}	1.2×10^{-5}	0			
343-4G			2954-2976	24	11	16	3	5.1×10^{-6}	8.6×10^{-6}	0			
556-25R			2129-2154	18	10	12	8	1.7×10^{-7}	0				
<u>Could & Devilwater Shale Member</u>	Middle to Late Miocene	Naval Petroleum Reserve #1, Elk Hills, California									6		Q
556-25R			2166	2	7.5	8	7	8.6×10^{-8}	0				
<u>Tombler Formation Media Shale Member</u>	Oligocene to Early Miocene	Naval Petroleum Reserve #1, Elk Hills, California									6		r
556-25R			2251-2263	8	19	22	17	6×10^{-8}	8.6×10^{-7}	0			

P Massive brown silty shale.

Q Siliceous shale sequence.

r Dark, silty foraminiferal shale, cherty shale, fine-grained sandstone.

REGION I (continued)

Geological Setting	Age	Locality	Depth (ft)	Number of Samples	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
					Pv.	Max.	Min.	Av.	Max.	Min.			
<u>Tasblor Formation</u> <u>Santos Shale Member</u>	Oligocene to Early Miocene	Naval Petroleum Reserve #1, Elk Hills, California									6		8
556-25K			2154	2	20	20		1.6×10^{-5}	1.0×10^{-5}	1.4×10^{-8}			
555-30R			3140	1	4	4		0	0				
<u>Fractured Shale Reservoirs</u> (cherty shale)	Miocene (Monterey)	Santa Maria District, California	No data	No data	6			$(8.6 \times 10^{-3} - 1.7 \times 10^{-3})$	3×10^{-2}		10, 11	Empirical determination calculated from production rates and history	t
<u>Shale</u>	Middle Miocene	San Luis Obispo County, California	No data	No data				3.4×10^{-10}			1	Streaming potential and SP log	u

^aLight-gray to tan and dark brown shale and siltstone.

^tFracturing the result of shrinkage during chemical changes.

^uMeasured using a 0.2N NaCl solution.

REGION I (continued)

Geological Setting	Age	Locality	Depth (ft)	Number of Samples	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
					Av.	Max.	Min.	Av.	Max.	Min.			
Shale in Stevensburg Sand	Miocene	South Coles Levee Field, California	2876-2877	1	8.0			8.6x10 ⁻⁹			7	Estimated from Region I data	v
Thunder Formation	Middle Miocene	Kettleman Hills, California	1905-2044	(many)	53						7		
Shale Sh-3	Upper Miocene	Kettleman North Dome Oil Field, California	6833-6838	1				2.9x10 ⁻¹¹			5	Measurements made on disaggregated sample in lab.	v
Shale Sh-6	Upper Miocene	Kettleman North Dome Oil Field, California	6833-6838	1				4.9x10 ⁻¹²			5	(Same as above)	x

^vBulk density.

^wMeasured at 3,000 psi compaction pressure.

^x6,000 psi compaction pressure.

REGION 1 (continued)

Geological Setting	Age	Locality	Depth (ft)	Number of Samples	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
					Av.	Max.	Min.	Av.	Max.	Min.			
<u>Shale</u> <u>Sh-9</u>	Upper Miocene	Kettleman North Dome Oil Field, California	6833-6838	1				0.1x10 ⁻³			5	(Same as above)	y
<u>Salinas Shale*</u>	Miocene	Goleta Landing, California	Outcrop		33.3			8.7x10 ⁻⁴			8	Estimated from Region 1 data	z
<u>Kr. -hagen Shal.</u>	Upper Eocene-Oligocene	North Belridge, California			3.9-4.3						1		

Y 9, si compaction pressure.

Z Dips 55°S, in stratum.

*Density: 1.78 g/cm³ dry; 2.11 g/cm³ sat.

**Density: 2.56-2.63 g/cm³ dry; 2.60-2.67 g/cm³ sat.

REGION 1 (continued)

Geological Setting	Age	Locality	Depth (ft)	Number of Samples	Porosity			Hydraulic Conductivity			Ref.	Determination Method	Notes
					Avg.	Max.	Min.	Avg.	Max.	Min.			
Solid Shale Body with a Few Fingers of Light Qtz Sand	Middle Eocene	Rio Vista Field, California	No data	No data	25						9	Laboratory estimate	aa
Terrigenous detrital sequence	Cambrian uppermost Pro-Cambrian	Yucca Flat, Nevada		10	2.0	3.6	0.7	9.5×10^{-11}	1.3×10^{-10}	1.3×10^{-11}	13	Effective porosity; mercury injection or water saturation methods. Permeability: lab test.	bb

aa In elongate dome trending NW-SE, has a very complicated fault pattern (Midland 5 zone).

bb Siltstone and argillite from well 89-68.

REGION I
OTHER PROPERTIES

Formation	Age	Locality	Flow Rate Ml/hr/1000 psi	Reference	Notes
<u>Shale</u>	Upper Miocene	Kettleman North Dome Oil Field, California Well #E5(29-21-17)		5	
Sh-3			6.4		Measured in lab at 3000 psi compaction pressure
Sh-6			12.1		Measured in lab at 6000 psi compaction pressure
Sh-9			2.25		Measured in lab at 9000 psi compaction pressure

REGION I

REFERENCES

1. Birch, F.; Schairer, J. R., and Spicer, C. H., 1942, Handbook of Physical Constants: Geological Society of America, Special Paper No. 36, 325 p.
2. Emery, K. O., and Rittenberg, S. L., 1952, Early Diagenesis of California Basin Sediments in Relation to Origin of Oil: Am. Assoc. Pet. Geol. Bull., v. 36, pp. 735-806.
3. Gondouin, M., and Scala, C., 1958, Streaming Potential and the SP Log: Trans. A.I.M.E., v. 213, p. 170-179.
4. Johnson, A. I.; Moston, R.P., and Morris, D. A., 1968, Physical and Hydrologic Properties of Water Bearing Deposits in Subsiding Areas of Central California: United States Geol. Surv. Prof. Paper 497-A, pp. 1-71.
5. Kharaka, Y. K. and Berry, F. A. F., 1973, Simultaneous Flow of Water and Solutes through Geological Membranes - I. Experimental Investigation: Geochimica et Cosmochimica Acta, v. 37, pp. 2577-2603.
6. Maher, J. C.; Carter, R. D., and Lantz, R. J., 1975, Petroleum Geology of Naval Petroleum Reserve No. 1, Elk Hills, Kern County, California: U. S. Geol. Surv. Prof. Paper 912, pp. 1-109.
7. Manger, E. G., 1963, Porosity and Bulk Density of Sedimentary Rocks: U. S. Geol. Surv. Bull. 1144-E, 55 p.
8. Melcher, A. F., 1924, Texture of Oil Sands with Relations to the Production of Oil: Bull. Am. Assoc. Pet. Geol., v. 8, pp. 716-774.
9. Railroad Commission of the State of California and Department of Natural Resources, Estimate of the Natural Gas Reserves of the State of California as of January 1, 1946: Case No. 4591, Spec. Study No. S-525.
10. Regan, Jr., L. J., 1953, Fractured Shale Reservoirs of California: Bull. Am. Assoc. Pet. Geol., v. 37, pp. 201-216.

REGION I: REFERENCES (continued)

11. Regan, Jr., L. J. and Hughes, A. W., 1949, Fractured Reservoirs of Santa Maria District, California: Bull. Am. Assoc. Pet. Geol., v. 33, pp. 32-51.
12. Rieke, Herman H. III and Chilingarian, George V., 1974, Compaction of Argillaceous Sediments: Developments in Sedimentology, v. 16, 424 p.
13. Winograd, I. J.; Thomderson, W., and Young, R. A., 1971, Hydrology of the Nevada Test Site and Vicinity, Southeastern Nevada: U. S. Geol. Surv. Open-File Report, 429 p.

REGION 2: ROCKY MOUNTAINS AND COLORADO PLATEAU

The region occupied by the Rocky Mountains and the Colorado Plateau corresponds to the eastern edge of the North American Cordillera. The area is part of a craton which felt the commotions of the continuous tectonic activity along the shores of the Pacific. The two zones responded rather differently: the Colorado Plateau by isostatic motion and the Rocky Mountains as an intra-cratonic folded mountain belt. During the Mesozoic, the Colorado Plateau became a landmass where thick continental units were piled up; while at the same time the Rocky Mountain was a zone of subsidence (e.g. the Denver Basin) where large accumulations of marine sediments were taking place. With the close of the Cretaceous and folding of the Rockies the whole region emerged and became a zone of deposition of continental shales rich in organic material (oil shales) (Eardley, 1962).

Three shale units can be distinguished:

- Triassic (Ankareh) and Jurassic (Morrison) shales are part of the continental sequence preserved in the Colorado Plateau region.

- Cretaceous shales are of two types: continental in the Colorado Plateau (Thermopolis), they are marine in the Rocky Mountain basins and extend into adjacent regions. The most continuous of all is the Pierre shale (Fig. 8).

- Cenozoic shales are continental and belong to the oil shale group, they are Eocene in age (Green River Formation).

Structural relationships involving these units are illustrated in Figure 9.

Figure 9: Structure sections showing typical relationships in the Colorado Plateau (top) and the Rocky Mountains (bottom). (After Earley, 1962)

TABLE 4-2 SUMMARY OF ROCK UNITS IN THE ROCKY MOUNTAINS; COLORADO PLATEAU AND GREAT PLAINS
[From Gill et al. (1970) and Lee (1927)]

NOTE: Shales described in the hydrologic tables are preceded by *.

Age		Stratigraphic Unit	Thickness (M)	Description
PLIOCENE		Ogallala Formation	0-213	Interbedded sand, siltstone, clay, lenses of gravel, thin limestone, and caliche
-----Unconformity-----				
EOCENE	Upper	Uinta Formation	183	Mudstones, sandstones, marlstones, and tuffs
	---	Bridger Formation	762	Marlstones, mudstone, claystone, sandstones, tuffs
	Middle	* Green River Formation	976	Oil shale, marlstone, minor sandstone and limestone
	---	Wasatch Formation		Carbonaceous shale, sandstone, conglomerate, lenticular coal beds
EOCENE TO PALEOCENE		* Fort Union Formation	1,220	Alternating shale and sandstone; basal conglomerate
PALEOCENE TO UPPER CRETACEOUS		* Lance Formation	230	Alternating shale and sandstone; lenticular sandstone beds

TABLE 4-2 (Continued)

Age		Stratigraphic Unit	Thickness (M)		Description
CRETACEOUS	Upper	* Pierre Shale	213	many equivalent units	Massive gray shale, <u>marine</u>
		Niobrara Formation	61		Fossiliferous limestone
		* Mancos Shale	915		Marine Shale
		* Graneros Shale	61		Massive, gray shale
	Lower	* Mowry Shale	46	Gray shales and thin-bedded sandstones	
		* Thermopolis Shale	213	Dark colored, flakey shales and shaly sandstones	
JURASSIC		* Morrison Formation	61		Variegated shale, irregular masses of sandstones, and few thin layers of limestone
TRIASSIC		* Ankareh Shale	-7-		Shale and sandy shale
-----Unconformity-----					
PERMIAN		* Rustler Formation	85-159		Anhydrite and rock salt with minor dolomite, sandstone, claystone and polyhyalite

Hydrologic Data

REGION II ROCKY MOUNTAINS, COLORADO PLATEAU, AND GREAT PLAINS

Geological Setting	Age	Locality	Depth (ft)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
						Av.	Max.	Min.	Av.	Max.	Min.			
<u>Lizard Formation</u>	Eocene	Southwest Wyoming												
Siltstone									6.8×10^{-5}	9.6×10^{-6}		7	Single and multiple hole permeability pumping tests	
Mudstone									1.0×10^{-3}					
<u>Green River Formation</u>	Eocene	Utah County, Utah	579.1-901.9	no data					4.4×10^{-7}			23	Based on transmissibility data	
Shale			579.1-905.7											
Shale			579.1-860.2						3.1×10^{-7}					
<u>Parachute Creek Member Green River Formation</u>	Eocene	Piceance Creek Basin, Colorado				20			1.9×10^{-3}	5.9×10^{-3}	6.1×10^{-4}	21, 22	Estimates of effective porosity (E) based on geologic estimation of salt amount originally in place in leached zone. Permeability based on transmissivity pumping tests.	

"Oil shale" $T_{min} = 7400$ gpd/ft; $T_{max} = 50,000$ gpd/ft; $T_{av} = 10,000$ gpd/ft. Thickness, max = 511, min = 400. Fracture porosity and permeability (leached zone). High fracture porosity caused by leaching of salts, remaining voids weakened.

REGION II (cont. from p. 1)

Geological Setting	Age	Locality	Depth (ft)	# of Samples	Density (gm/cm ³)	Porosity	Hydraulic Conductivity (cm/s)		Ref.	Determination Method	Notes
							Avg.	Max.			
Delta and Green River Formation	Eocene	Picance Basin, Colorado							7		
Siltstone-Shale							2.1×10^{-4} (H) 2.1×10^{-5} (V)				
Siltstone-Shale							2.1×10^{-5} (H) 1×10^{-6} (V)				
Oil Shale-Pentz Zone											
Upper Patashute Creek						H	2×10^{-5}			Laboratory test	
Alhambra						B	1.5×10^{-4}				
Lower Patashute Creek							1.2×10^{-5}				
Leached Zone						H	2.1×10^{-5}				
Garden ditch						G	2.8×10^{-5} 2.3×10^{-5}				
Silty Carbonaceous Shale	Eocene	Northwest Colorado					1.2×10^{-7}		7	(see above)	

b = $\pm$ 20% accuracy. H = horizontal, V = vertical.

REGION II (continued)

Geological Setting	Age	Locality	Depth (ft)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
						Av.	Max.	Min.	Av.	Max.	Min.			
<u>Uta and Green River Formation</u>	Eocene	Piceance Basin, Colorado												
Shale									2×10^{-6} (H) 1×10^{-6} (V)			7	Single and multiple hole permeability pumping tests	b
Siltstone-Shale									1.5×10^{-4} (H) 3×10^{-5} (V)					
Shale									1.2×10^{-5} (H) 1×10^{-7} (V)					
<u>Shale</u>	Cenozoic	Piceance Basin, Colorado		1	1.86				1.5×10^{-5}			20	Lab	c
				1	2.10				7.6×10^{-6}					d

^b $\pm$ 20% accuracy. H = horizontal, V = vertical.

^c in situ. Room permeability 1.3×10^{-5} cm/sec.

^d in situ. Room permeability 9.4×10^{-6} cm/sec.

REGION II (continued)

Geological Setting	Age	Locality	Depth (ft)	N of Sample	Non-silty (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes	
						Av.	Max.	Min.	Av.	Max.	Min.				
<u>Fort Union Formation</u>															
Eocene	Rosebud County, Montana			dry	1.71	36.6						3			
				sat	1.01										
				dry	1.67-2.06										
				sat	2.04-2.29	21.5-36.9									
<u>Fort Union Formation</u>															
Eocene	Rosebud County, Montana		outcrop (?)	1	2.07	21.2						12			
				outcrop	2	1.87	30.2	36.9	23.5						
<u>Fort Union Formation</u>															
Eocene	Rosebud County, Montana				2.06	23.5						17			
				sub-surface	1	1.67	36.9								
					1	1.91	26.2								

^atotal porosity.

REGION II (continued)

Geological Setting	Age	Locality	Depth (ft)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
						Avg.	Max.	Min.	Avg.	Max.	Min.			
<u>Fort Union Formation</u> Lebo Shale Member	Eocene	Rosebud County, Wyoming		dry 2.07 sat 2.28		21.2						3		
<u>Knight Formation</u>	Eocene	Afton Quadrangle, Wyoming										3		
Sand Clay				dry 1.99 sat 2.22		23.1								
Siltstone				dry 2.32 sat 2.43		11.1-15.4								
<u>Lance Formation</u>	Tertiary (?)	Rosebud County, Montana										17		
Shale				1	1.65	40.1			2.3×10^{-2}					
Tullock Member (Shale)				1	1.92	29.0			7.2×10^{-3}					

REGION 11

Geological Setting	Age	Locality	Depth (ft.)	# of Samples	Density (gm/cm ³)	Porosity		Hydraulic Conductivity (cm/s)		Ref.	Determination Method	Notes
						Nv.	Max. Min.	Av.	Max. Min.			
Graneros Shale (slightly weathered)	Upper Cretaceous	Hamilton County, Kansas	Outcrop	2	1.98	24.9	25.2 24.6	1x10 ⁻⁸		11	Melcher method	
			921-926	1	2.39	11.6	4.5x10 ⁻¹¹		11	(see above)	f	
			1202-1204	2	2.35	10.1 11.0 9.2	2.2x10 ⁻¹¹					
			1367-1370	1	2.41	8.9	1.4x10 ⁻¹¹					
			1462-1465	1	2.52	9.6	1.9x10 ⁻¹¹					
			1523-1526	1	2.45	8.7	1.7x10 ⁻¹¹					
Graneros Shale	Upper Cretaceous	Hamilton County, Kansas	1626-1634	2	2.52	8.2 8.4 7.9	8.6x10 ⁻¹²		11	(see above)	g	
			1657-1658	1	2.52	8.1	8.6x10 ⁻¹²					

f Ransom well.

g Vertical succession.

h Well cuttings.

REGION 11 (continued)

Geological Setting	Age	Locality	Depth (ft)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Rel.	Determination Method	Notes
						Av.	Max.	Min.	Av.	Max.	Min.			
<u>Shale</u>	No data	Phillips County, Kansas	427	2	2.15	22.0						11		j
			453	2	2.15	22.7	22.1	23.3						
			785	2	2.31	17.1	16.5	17.8						
<u>Green Horn Formation</u>	Upper Cretaceous	Black Hills, Wyoming	≈1524	no data		37.6						16		j
<u>Niobrara Formation</u> (Heaver Creek Chalky Member)	Upper Cretaceous	Black Hills, Wyoming	1631	no data		25.4								k
<u>Colorado Shale</u>	Upper Cretaceous	Bowdoin Dome, Montana	-	no data		10			1.0x10 ⁻¹¹			1	Measured	l

j Phillips well.

j Marl, 1° dip.

k Marl, 10° dip, close to a fault.

l Sometimes referred to as a very fine grained tight sand. Drillers log - producing Zone A shale.

REGION II (continued)

Geological Setting	Age	Locality	Depth (ft)	# of Samples	Density (gm/cm ³)	Porosity		Hydraulic Conductivity (cm/s)		Ref.	Determination Method	Notes
						Avg.	Max.	Min.	Avg.			
Upper Skull Creek Number	Lower Cretaceous	Third Creek Area, Denver Basin, Colorado		3		1.4	1.8	0.5	3.4×10^{-13}	15	Petrographic techniques	m
Cody Shale	Upper Cretaceous	Powder River Basin, Wyoming		13					1×10^{-5}	13	Not stated	n
Shale	Unknown	Nevas, Montana	2155			9.5			(1) 5.1×10^{-10} (2) 6×10^{-12} (3)	8	Streaming Potential and SP log	o
	Unknown	Heavenweep, Utah	1793			4.6						
	Cretaceous	Snyder, Nebraska				12.7			3.4×10^{-9}			

^m Highly variant, fine grained unies.

ⁿ Thick, rippled, very fine grained sandstone and shale enveloped entirely in gray shale.

^o (1) 0.02N NaCl

(2) 0.2N NaCl

(3) 1N NaCl

REGION II (continued)

Geological Setting	Age	Locality	Depth (ft)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
						Av.	Max.	Min.	Av.	Max.	Min.			
<u>Bentonite</u>	?	Wyoming		1		34			4×10^{-12} ^a			4	lab	r
<u>Shale</u>	?	New Mexico							1.7×10^{-12}			16	lab	r
<u>Shale</u>	?	Fallon County, Montana			dry 1.79 sat 2.08	28.8			1.4×10^{-8} ^a			1		
{Bentonite}	?	Utah							4.5×10^{-11}			15	lab.	r
		Wyoming				34			3.4×10^{-12}					
		Wyoming				41			4.3×10^{-12}					
<u>Shale and Siltstone</u>	Cretaceous	Iane, Nebraska	1415			7.0	2.5		5.3×10^{-12}	5.3×10^{-13}		9	Gamma ray attenuation	

^a 2.5N NaCl solution as permeant... Compaction load 2.76×10^{10} dynes/cm².

^b 0.2N NaCl solution as permeant.

^c Sodium-water permeant, 7 psi.

^d 40,000 psi load.

REGION 11 (continued)

Geological Setting	Age	Locality	Depth (ft)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
						Av.	Max.	Min.	Av.	Max.	Min.			
Carlisle Shale Turner Sandy Member	Upper Cretaceous	Winton County, Wyoming	~1768	1	2.00	23.8						16		t
Niobrara Formation Sage Breaks Shale Member	Upper Cretaceous	Winton County, Wyoming	~1692	1	1.99	25.3						16		u
Hilliard Formation (Shale)	Cretaceous	Afton Quadrangle, Wyoming	cut- (?)		1.98-2.28	26.9	13.8					12		c
Mayan Formation	Cretaceous	Afton Quadrangle, Wyoming												
Clay					1.0	25.3						12		c
Hudstone					1.9	28.6								

^aTotal porosity.

^bGray shale; dip 31°SW.

^cGray shale; dip 50° S.

REGION II (continued)

Geological Setting	Age	Locality	Depth (ft)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
						Av.	Max.	Min.	Av.	Max.	Min.			
<u>Bear River Formation</u>	Upper Cretaceous	Afton Quadrangle, Wyoming										3		
Siltstone				dry	2.47									
				sat	2.54	7.4								
Shale				dry	2.64									
				sat	2.65	1.3								
<u>Frontier Formation</u>	Upper Cretaceous	Afton Quadrangle, Wyoming		dry	1.89							3		
				sat	2.11	22.1								
<u>Bearpaw Shale</u>	Upper Cretaceous	Rosebud County, Montana		1	1.57	41.1						17		
<u>Judith River Formation (Sandy Shale)</u>	Upper Cretaceous	Rosebud County, Montana		1	1.54	44.0						17		
<u>Mancos Shale</u>	Upper Cretaceous	Black Mesa, Arizona							4.6×10^{-6}	4.6×10^{-10}		5	Hydrologic laboratory studies (measured)	v

^v Vertical measurements only. Travel time for contaminants 126-1,260,000 years.

REGION 17 (continued)

Geological Setting	Age	Locality	Depth (ft)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
						Av.	Max.	Min.	Av.	Max.	Min.			
<u>Claggett Shale</u>	Upper Cretaceous	Rosebud County, Montana		1	1.81	36.3						17		
<u>Cody Shale</u>	Upper Cretaceous	Gebo Oil Field, Hot Springs County, Wyoming	220-404		2.53	9.1	[1.7%]*					2		w
<u>Mowry Shale</u>	Lower Cretaceous	Gebo Oil Field, Hot Springs County, Wyoming	569-678		2.44	14.4	[1.6%]*					2		w
<u>Thermopolis Shale</u>	Lower Cretaceous	Gebo Oil Field, Hot Springs County, Wyoming	740-781		2.52	9.7	[1.8%]*					2		w
Shell Creek Member			678-733		2.44	14.6	[1.7%]*							

*Porosity and density calculated from borehole gravity survey.

*Porosity uncertainty.

REGION 11 (continued)

Geological Setting	Age	Locality	Depth (ft)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
						Av.	Max.	Min.	Av.	Max.	Min.			
<u>Graham</u> <u>Shale</u>	Upper Cretaceous	Crook County, Wyoming												
Skull Creek Member			~2164	1	1.87	32.5						16		x
Nelle Fourche Member			~1615	1	1.78	33.3								y
<u>Pierre</u> <u>Shale</u>	Upper Cretaceous													
Gannon Ferruginous Member		Crook County, Wyoming	~1509	1	2.04	26.0						16		z
Mitten Black Shale Member		Weston County, Wyoming	~1311	1	1.56	35.8								aa
Upper Part			~1113	1	1.96	25.4								bb
* Black shale; dip 5° SW.						z Dip 5° SW.								
y Black shale; dip 4° NE.						aa Dip 45° SW.								
						bb Gray shale; dip 33° SW.								

REGION II (continued)

Geological Setting	Age	Locality	Depth (M)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
						Avg.	Max.	Min.	Avg.	Max.	Min.			
<u>Pierre Shale</u>	Cretaceous	Cimarron, New Mexico							2.5×10^{-11}			19	Not stated	
		North and South Dakota, Colorado							1×10^{-10}			18	Not stated	cc
<u>Pierre Shale</u>	Cretaceous					71			9.4×10^{-11}			15	Lab	
<u>Muddy Shale</u>	Cretaceous					4.7			4.3×10^{-8}			15	Lab	
<u>Colorado Shale</u>	Upper Cretaceous	Fergus County, Montana			dry 2.07 sat 2.30	22.6			5.8×10^{-9}			3		
<u>Muddy Shale</u>	Cretaceous	Logan County, Colorado	1490	13		Before deformation: 4.1-5.1% After deformation: 4.4-10.9%			8.58×10^{-9} to 2.49×10^{-7}			9	Lab.	

cc A regional permeability value repository for cool (400°F) waste.

REGION II (continued)

Geological Setting	Age	Locality	Depth (ft)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
						Av.	Max.	Min.	Av.	Max.	Min.			
<u>Adaville Formation</u>	Cretaceous	Afton Quadrangle, Wyoming	outcrop	2	2.07	23.0						12		dd
Mudstone			outcrop		2.34	11.9								
Shale		Sublette County, Wyoming	4151	1		7.8							Lab.	ee
Shale			1474	1		5.7			$< 8.58 \times 10^{-8}$				Lab.	ff
<u>Cloverly Formation</u>	Lower Cretaceous	Gebo Oil Field, Hot Springs County, Wyoming	781-794		2.44	14.2	[2.11]*					2		gg
<u>Morrison Formation (Claystone)</u>	Jurassic	Long Park, Colorado	62-75	6		16.5	20.3	8.8				12		hh

dd Total porosity.

ee Effective porosity.

ff From borehole gravity survey.

REGION 11 (continued)

Geological Setting	Age	Locality	Depth (M)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/g)			Ref.	Determination Method	Notes
						Av.	Max.	Min.	Av.	Max.	Min.			
<u>Ankareh Siltic</u>	Triassic	Alton Quadrangle, Wyoming	out-crop		2.40	9.2						12		dc
<u>Woodside Formation (shale)</u>	Triassic	Alton Quadrangle	out-crop		2.24	16.1						12		dd
<u>Crow Mountain Sandstone (Upper siltstone)</u>	Upper Triassic	Gobo Oil Field, Hot Springs County, Wyoming	1107-1111		2.59	5.4	{2.6%}	*				2		gg
			1111-1115		2.46	11.7	{2.2%}	*						
			1115-1128		2.55	7.0	{2.1%}	*						
<u>Red Peak Formation (Calcareous red siltstone and claystone)</u>	Lower Triassic	Gobo Oil Field, Hot Springs County, Wyoming	1134-1247		2.67	1.6	{1.2%}	*				2		gg
			1247-1347		2.63	3.9	{1.8%}	*						
			1347-1371		2.74	1.9	{2.0%}	*						

*Porosity uncertainty.

dd Total porosity.

gg From borehole gravity survey.

REGION 11 (continued)

Geological Setting	Age	Locality	Depth (ft)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
						Av.	Max.	Min.	Av.	Max.	Min.			
<u>Bustler Formation</u>	Permian	Eddy County, New Mexico										6		
Tamarisk Member (Claystone)			147		2.08	22.1								
Forty-Miner Member (Siltstone)			101		2.00	24.9								
Lower Member (Claystone)			160		1.91	29.6								
			168		2.01	25.1								
Lower Member (Siltstone)			100		2.13	21.3								
			189		2.17	19.3								
<u>Bentonite</u>	?	Wyoming							2.8×10^{-9}			15	Lab.	hh
		Utah							7.2×10^{-7}					

hh Calcium-water solution used as permeant at 7 psi.

REGION II (continued)

Geological Setting	Age	Locality	Depth (M)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
						Av.	Max.	Min.	Av.	Max.	Min.			
<u>Gros Ventre Formation</u>	Cambrian	Afton Quadrangle, Wyoming	out-crop		2.38	11.1						12		ii
<u>Ophir Formation</u>	Cambrian	Ophir, Utah												
Shale			subsurface	1	2.81	0.9						12		jj
Silicified Shale			subsurface	1	2.8	0.6								

ii Total porosity.

jj Effective porosity.

REGION II
OTHER PROPERTIES

Formation	Age	Locality	Depth (M)	No. of Samples	Compressive Strength (lbs/in ²)	Ultimate Strength (bars)	Resistivity (ohm M ² /M)	Ref.
<u>Ophir Formation</u> (Shale)	Cambrian	Ophir, Utah	Sub- surface	2	31,300			12
(Silicified Shale)			Sub- surface	1	33,500			
<u>Muddy Shale</u>	Cretaceous	Logan County, Colorado	1490	13		400-4170		9
<u>Cody Shale</u>	Upper Cretaceous	Gebo Oil Field, Hot Springs County, Wyoming	220- 404				Range: 4-9 Ave: 5	2
<u>Mowry Shale</u>	Lower Cretaceous	Gebo Oil Field, Hot Springs County, Wyoming	569- 678				Range: 3-22 Ave: 8	2
<u>Thermopolis Shale, Shell Creek Member</u>	Lower Cretaceous	Gebo Oil Field, Hot Springs County, Wyoming	678 733				Range: 2-6 Ave: 4	2

REGION II: OTHER PROPERTIES (continued)

Formation	Age	Locality	Depth (M)	No. of Samples	Compressive Strength (lbs/in ²)	Ultimate Strength (bars)	Resistivity (ohm M ² /M)	Ref.
<u>Thermopolis Shale</u>	Lower Cretaceous	Gebo Oil Field, Hot Springs County, Wyoming	740- 794				Range: 3-14 Ave: 5	2
<u>Cloverly Formation</u>	Lower Cretaceous	Gebo Oil Field, Hot Springs County, Wyoming	781- 794				Range: 3-6 Ave: 4	2
<u>Crow Mountain Sandstone- Upper Siltstone</u>	Upper Triassic	Gebo Oil Field, Hot Springs County, Wyoming	1107- 1111 1111- 1115 1115- 1128				Range: 20-25 Ave: 23 Range: 19-30 Ave: 25 Range: 30-36 Ave: 33	?
<u>Moencopie Shale</u>		Meteor Crater, Arizona					2×10^{-4} ohm-cm	3

REGION II

REFERENCES

1. Bartram, J. G., and Erdmann, C. E., 1935, Natural Gas in Montana, in Ley, H. A. (ed.), Geology of Natural Gas: Amer. Assoc. Pet. Geol., Tulsa, pp. 245-276.
2. Beyer, L. A. and Clutsom, F. G., 1978, Density and Porosity of Oil Reservoirs and Overlying Formations from Borehole Gravity Measurements, Gebo Oil Field, Hot Springs County, Wyoming: Oil and Gas Investigations, U. S. Geological Survey, Chart OC-88.
3. Birch, F.; Schaller, J. R., and Spicer, C. H., 1942, Handbook of Physical Constants: Geological Society of America, Special Paper No. 36, 325 p.
4. Bredehoeft, J. D. and Hanshaw, B. B., 1968, On the Maintenance of Anomalous Fluid Pressures - I. Thick Sedimentary Sequences: Geological Society of America Bulletin, v. 79, no. 9, pp. 1097-1106.
5. Dove, A. H. and Roefs, T. G., 1973, Competitive Groundwater Usage from the Navajo Sandstone: Hydrol. Water Resources Ariz. Southwest, v. 3, p. 124-135.
6. Gard, L. M. Jr., 1968, Geologic Studies, Project Gnome, Eddy County, New Mexico: U. S. Geol. Survey Professional Paper 589.
7. Golder Associates, 1977, Second Study, Development of Site Suitability Criteria for a High Level Waste Repository: A Report to Lawrence Livermore Laboratory, UCRL-13793, 440 p.
8. Gondouin, M., and Scala, C., 1958, Streaming Potential and the SP Log: Trans. A.I.M.E., v. 213, p. 170-179.
9. Handin, J.; Hager, R. V., Jr.; Friedman, M., and Feather, J. N., 1963, Experimental Deformation of Sedimentary Rocks Under Confining Pressure: Pore Pressure Tests: American Association of Petroleum Geologists Bulletin, v. 47, no. 5, pp. 717-755.
10. Harms, J. C., 1966, Stratigraphic Traps in a Valley Fill, Western Nebraska: Am. Assoc. Pet. Geol. Bull., v. 50, p. 2119-2149.

REGION II: REFERENCES (continued)

11. Hedberg, H. D., 1926, The Effect of Gravitational Compaction on the Structure of Sedimentary Rocks: Bull. Am. Assoc. Pet. Geol., v. 10, pp. 1035-1072.
12. Manger, E. G., 1963, Porosity and Bulk Density of Sedimentary Rocks: U. S. Geological Survey Bulletin 1144-E, 55 p.
13. Martinsen, R. S., and Tillmal, R. W., 1978, Hartzog Draw, New Giant Oil Field: Amer. Assoc. Pet. Geol. Bull., v. 62, p. 540.
14. Reinert, S. L., and Davies, D. K., 1976, Third Creek Field, Colorado: A Study of Sandstone Environments and Diagenesis: Mountain Geol., v. 13, pp. 47-60.
15. Rieke, Herman H. III, and Chilingarion, George V., 1974, Compaction of Argillaceous Sediments: Developments in Sedimentology, v. 16, 424 p.
16. Rubey, W. ..., 1930, Lithologic Studies of Fine-Grained Upper Cretaceous Sedimentary Rocks of the Black Hills Region: U. S. Geol. Surv., Prof. Paper 165-A, pp. 1-54.
17. Stearns, N. D., 1927, Laboratory Tests on Physical Properties of Water-Bearing Materials: U. S. Geological Survey Water Supply Paper 596, pp. 121-176.
18. Shurp, G. W., and Bredehogdal, J. D., 1977, The Pierre Shale as a Possible Waste Repository Abstr: Geol. Soc. Amer. Abstr. Programs, v. 9, no. 7, p. 1174.
19. Summers, W. K.; Balgstrom, R. E.; Walker, C. W., and Hammock, G., 1977, Hydrogeologic Investigation for Low-Level Radwaste Disposal Near Cimarron, New Mexico: Geol. Soc. Amer. Abstr. Programs, v. 9, no. 7, p. 1193-1194.
20. Thomas, C. W., 1966, Some Effects of Overburden Pressure on Oil Shale During Underground Retorting: Society of Petroleum Engineers Journal, v. 6, no. 1, pp. 1-8.
21. Weichman, B. E., 1974, Some Effects of the Rio Blanco Nuclear Detonation on the Leached Zone in the Parachute Creek Member of the Green River Formation: Rocky Mt. Assoc. Geol. Field Conf. Guide, no. 25, Guidebook to the Energy Resources of the Piceance Creek Basin, Colorado, p. 205-215.

REGION II: REFERENCES (continued)

22. Weichman, B. E., 1975, Depositional History and Hydrology of the Green River Oil Shale, Piceance Creek Basin, Rio Blanco County, Colorado: A.I.M.E. Trans, v. 256, p. 272-277.
23. Weir, J. E., 1970, Geohydrology of the Area Near Wosco, Exploratory Hole Number 1, Uintah County, Utah, U. S. Geol. Surv. Open-File Report, 27 p.

REGION 3: THE MID CONTINENT

The Mid Continent region is broadly spread between the Rocky Mountains and the Appalachians and the Canadian Shield and the Gulf Coast. It is a craton which underwent some deformation at the end of the Paleozoic in its southern portion (Eardley, 1962) forming numerous domes and basins (Fig. 10). This is the common setting for the Chattanooga Shale (Fig. 11). During the Mesozoic the region was invaded by epicontinental seas where extensions of Rocky Mountain units (e.g. equivalents of the Pierre shale) were deposited.

Examples of the simple structural relationships characterizing the Mid Continent are shown in Fig. 12.

Figure 10: Distribution of Paleozoic structures in the Mid-Continent and Great Plains Regions (From Mintz, 1977)

Figure 11: Map showing the distribution of the Chattanooga Shale (Devonian-Mississippian) in the United States (From Mintz, 1977). Darker shades show present extent of the unit.

Figure 12: Sections illustrating structural relationships in the Mid-Continent and Great Plains regions. Top: Great Plains, Middle: Denver Basin, Bottom: Paleozoic Basins and domes (from King, 1951)

TABLE 4-3 SUMMARY OF ROCK UNITS FROM THE MID-CONTINENT REGION
[From Ruedeman (1939)]

NOTE: Shales described in the hydrologic tables are preceded by *.

Age	Stratigraphic Unit	Thickness (M)	Description
TERTIARY	{See Table 3-2 for details.}		
MESOZOIC			
PERMIAN	PERMIAN RED BEDS		
	Quartermaster, Big Basin Formation	91-152	Soft, red sandstone, sandy clays and shales
	Cloud Chief Hackberry Group	0-35	Massive white-pink gypsum, irregularly bedded with red clay shales
	Woodward Group	91-129	Red clay shales, dolomite, red sandstones, conglomeritic sandstones
	Blaine Gypsum	23	Massive white gypsum separated by beds of red clay shale and dolomite
	Enid Group	366-457	Red clays and shales with occasional sandstone beds. Gypsiferous.
	Asher Formation	76	Coarse red-gray sandstones and red-clay shale
	SUMNER GROUP		
	* Wellington Formation	183-207	Bluish-gray, greenish and red shales, thin sandstone beds, important salt beds in lower section
	Marion Formation	122-152	Buff, thin-bedded limestones and thick shale beds
	CHASE GROUP	73-91	Interbedded limestones and shales with minor flint

TABLE 4-3 (Continued)

Age	Stratigraphic Unit	Thickness (M)	Description
PERMIAN	Council-Grove Group	46	Massive shales, sandy limestones, yellow shales and thin limestones
	Eskridge Shale	12-23	Green, brown, or yellow shales
	Neva Limestones	3-6	Massive gray limestone, one thin shale parting
PENNSYLVANIAN	Wabaunsee Group	152	Eight members, shales, sandstones and limestones
	Shawnee Group	111-152	Nine members, cherty-argillaceous shales, limestones, sandstones, some coal beds
	Douglas Group	107-167	Four members including <u>Weston Shale</u> . Sandstones, argillaceous shales and limestones.
	Lansing Group	38-76	Four members. Clayey to sandy shales and massive limestone
	* Chanute Shale	8-31	Clay shale to sandy shale
	* Cherokee Formation	137-305	Variable colored shales with considerable lithologic variation
	* Adair Formation	60-2,134	Shales with lenses and thin ledges of brown sandstone
	Wapanucka Limestone	0-244	Limestone, chert, sandstone, and shale.

TABLE 4-3 (Continued)

Age	Stratigraphic Unit	Thickness (M)	Description
MISSISSIPPIAN	Barnett Shale	0-15	Black shales and slates with a basal limestone member
	Jack Fork Formation	0-2,012	Gray sandstones with dark shales at wide intervals
	* Stanley Shale	244-762	Irregularly bedded sandstones, shales, and slates
	Caney Shale	0-488	Black shales and slates with limestone lentils; blue shales with sandy members
	Pitkin Limestone	0-43	Rusty brown shaly strata to fine-textured, massive, bluish beds
	Mayes Formation	0-40	Contains <u>Fayetteville Shale</u> . Bituminous shale, limestone, sandstone
	Boone Limestone	18-168	Interstratified chert and cherty limestone
	* Chattanooga Shale	2-70	Black, slaty, bituminous shale; basal sandstone unit.
DEVONIAN- MISSISSIPPIAN	Sycamore Limestone	0-152	Hard slaty, blue limestone
	* Woodford Chert	61-213	Limy chert with shales
	Arkansas Novaculite	76-183	White to black novaculite thin to massive; slates
DEVONIAN	HUNTON FORMATION		
	Bois d'Arc Limestone	0-27	White to gray crystalline limestone with thin beds of chert
	Haragan Shale	0-51	Soft marly shaly, gray to drab color with interbedded marly limestone

TABLE 4-3 (Continued)

Age		Stratigraphic Unit	Thickness (M)	Description
SILURIAN		HUNTON FORMATION		
		Henryhouse Shale	0-68	Gray to drab-colored shales and soft marly limestone
		Chimney Hill Limestone	0-16	Pink, crinoidal and oolitic limestone
		St. Clair Marble	0-61	Pinkish white, coarsely crystalline marble
		Blaylock Sandstone	244-457	Gray, hard sandstone and interbedded shaly sandstone
		Talihina Chert	366	
ORDOVICIAN	Upper	Cason Shale	uncertain	
		Fernvale Limestone	uncertain	Gray, crystalline, fossiliferous limestone
		* Sylvan Shale	18-91	Green to green-blue
		Polk Creek Shale	30	Black graphitic shales
		Tyner Formation	18-79	Sandstone, shale, calcereous cherty limestones
	Upper to Middle	Viola Limestone	0-288	Massive, heavy-bedded homogeneous limestone
		Jasper Limestone	0-15	Noncrystalline limestone with considerable sandstone
		Joachim Limestone	29	Fine crystalline Mg limestone with quartz sandstone
		Big Fork Chert	152-244	Gray to black chert and ledges of cherty fossiliferous limestones

TABLE 4-3 (Continued)

Age		Stratigraphic Unit	Thickness (M)	Description
ORDOVICIAN	Upper to Middle	Womble Schistose Sandstone	76-305	Micaceous, fine-grained sandstone interbedded with shales
		Blakely Sandstone	0-15	Gray sandstone and black and green shale
	Lower	Simpson Group	61-976	Sandstones, thin limestones interbedded with greenish clay, shales and marls
		St. Peter Sandstone	0-61	Fine-grained, poorly cemented sandstone
		YELVILLE FORMATION		
		Everton Limestone	0-30	Fine-grained limestone, basal sandstone
		Powell Limestone	0-61	Mg-Limestone, shale, basal conglomerate
		Cotter Dolomite	152	Fine-grained, argillaceous dolomite; massive medium-grained with shale and sandstone
		Jefferson City Dolomite	183	
		Mazarn Shale	305	Dark, carbonaceous hard clay shales and slates
		Crystal Mt. Sandstone	259	Uniform, medium-grained, massive sandstone. Basal conglomerate
		Arbuckle Limestone	1,525-1,829	Thin-bedded to massive Mg-Limestone

TABLE 4-3 (Continued)

Age	Stratigraphic Unit	Thickness (M)	Description
CAMBRIAN	Reagan Sandstone	0-152	Coarse, granitic sandstone to limey shale
	Ellenburger Limestone	610	Crystalline dolomite
	Wilberns Formation	61	Sandy, thin-bedded limestones; shale
	Cap Mountain Formation	27	Glaucanite Limestone and sandstone
	Hickory Sandstone	0-107	Conglomerate
	Collier Shale	61	Metamorphosed, graphitic, black shales capped by thin-bedded limestones
PRECAMBRIAN	Basement Complex		Gneiss, schists, crystalline limestone and other metamorphic sedimentaries and plutonic rocks.

Hydrologic Data

REGION III Mid Continent Region

Geological Setting	Age	Locality	Depth (ft)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
						Avg.	Max.	Min.	Avg.	Max.	Min.			
<u>Wollington Shale</u> (calcereous)	Permian	Salina, Kansas		2	2.39	15.4	15.5	15.3				5	Jolby balance	a
<u>Mentor Beds</u> (Black Shale)	(Cretaceous) Paleocene	Falun, Kansas		2	2.06	23.1	23.3	22.9				5		a
<u>Chazy Shale</u>	Pennsylvanian	Lynn Well, Montgomery County, Kansas	152-154	2	2.47	10.4	10.6	10.2				5		a
			297	2	2.54	7.8	8.2	7.3						
			396-398	3	2.53	7.8	8.5	7.1						
<u>Fractured Black Carbonaceous Shales and Silty Shales</u>	Middle Permian	Dawson County, Texas	no data	no data		8			4.3x10 ⁻⁷			12	Micrometer gauge measured	b

^a Averages from vertical sequences.

^b Induced fracturation to conduct oil to well bore.

REGION 111 (Continued)

Geological Setting	Age	Locality	Depth (M)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
						Av.	Max.	Min.	Av.	Max.	Min.			
<u>Shales</u>	Permian	Thomas Pool, Oklahoma	Surface			20						1	Not stated	
<u>Shales</u>	Pennsylvanian	Ponca City and Garber Pools, Oklahoma	150		2.13	38						1	Graph	c
			300		2.24	31								
			1220		2.57	8								
			1830			4								
<u>Chanute Shale</u>	Pennsylvanian	Independence, Kansas	Outcrops (mines, quarries, shale pits)	2	2.31	14.9	15.0	14.8				5	Jolly balance method	d
<u>Wegton Shale</u>	Pennsylvanian	Honner Springs, Kansas		2	2.28*	15.8	16.0	15.5				5	*	

^c Extrapolated from graph, depth vs. % porosity.

^d From areas of little or no deformation.

$$* \left[1 - \frac{\text{rock density}}{\text{mineral density}} (\text{dry}) \times 100 = \% \text{ porosity} \right]$$

REGION III (continued)

Geological Setting	Age	Locality	Depth (ft)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination method	Notes
						Av.	Max.	Min.	Av.	Max.	Min.			
<u>Cherokee Shale</u>	Pennsylvanian	Oklahoma City, Oklahoma										7	Core analysis	
Phillips Well 1			1606	3		17	19	15						
Phillips Well 2			1604-1612	5		21	23	19						
Phillips Well 1			1611-1614	8		19	22	15						
Phillips Well 7			1620	5		18	23	10						
Phillips Well 2			1589-1604	21		18	21	11						
Well E				5		12.7			1.2x10 ⁻⁴					e
<u>Shales</u>	Pennsylvanian	Kansas-Oklahoma region							9.5x10 ⁻⁵	1.0x10 ⁻⁵		11	Streaming potential and SP log	
<u>Shale</u>	Pennsylvanian	Stockholm, Oklahoma	1267			11.6			6.9x10 ⁻¹⁰			4	(see above)	f
<u>Shale</u>	Pennsylvanian	Williams, New Mexico	3426			3.8			1.7x10 ⁻¹²			4	(see above)	f

^e Newly constructed well.

^f 0.2N NaCl.

REGION III (continued)

Geological Setting	Age	Locality	Depth (ft)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
						Avg.	Max.	Min.	Avg.	Max.	Min.			
<u>Shale</u>	Pennsylvanian	Hobbs Wildcat, New Mexico	2623			7.0						4	Direct measurement with a gas porosimeter	
<u>Shale</u>	Pennsylvanian	Reagan County, Texas				6.2						4		
<u>Shales and Siltstones</u>	Permian	Paduca, New Mexico	1412			20				4.3×10^{-6}		2		g
<u>Stanley Sandstone</u>	Pennsylvanian	Ouachita Mountains, Arkansas and Oklahoma				26	0.5		2×10^{-5}	4.3×10^{-6}		9		h

^gGentle homocline, dips to east. Turbidite sequence.

^hInterbedded shales and sandstones.

REGION III (continued)

Geological Setting	Age	Locality	Depth (ft)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
						Avg.	Max.	Min.	Avg.	Max.	Min.			
<u>Shale</u>	Pennsylvanian and Permian	Ponca City and Garber Areas, Oklahoma	305		2.25	17						8	Direct measurement with a gas porosimeter	
			610		2.42	11								
			914		2.52	7								
			1219		2.57	5								
			1524		2.62	4								
<u>Burgess Sandstone (Shale)</u>	Pennsylvanian	South Moore Pool, Oklahoma	2381-2384			3-4						8		
<u>Shale (Weathered)</u>	?	Near Ponca City, Oklahoma					48	37				8		
<u>Clay</u>	?	Near Ponca City, Oklahoma				53						8		1
<u>Shale</u>	?	Oklahoma							6.9x10 ⁻¹⁰			10	Lab.	1

¹Effective porosity.

²0.2M NaCl solution used as permeant.

REGION III (continued)

Geological Setting	Age	Locality	Depth (M)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
						Av.	Max.	Min.	Av.	Max.	Min.			
<u>Shale</u>	?	Northern Oklahoma			dry 2.15 sat <2.15	<20						3		
<u>Shale</u>	?	Northern Oklahoma			dry >2.55 sat 2.59	<4						3		
<u>Stanley Shale</u>	Pennsylvanian	Ouachita Mountains, Oklahoma			2.45-2.60 dry 2.52-2.62 sat	2.5-6.8						3		
<u>Fayetteville Shale</u>	Mississippian	Ozark Plateau, Oklahoma			2.27-2.44 dry 2.41-2.53 sat	8.6-14.1						3		
<u>Sylvan Shale</u>	Ordovician	Murray County, Oklahoma	outcrop	8		39.94-43.30						6	Lab.	k

^kDistribution coefficients available in reference 6.

REGION III (continued)

Geological Setting	Age	Locality	Depth (M)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
						Av.	Max.	Min.	Av.	Max.	Min.			
<u>Shale</u>	7	Phillips Well, Russell County, Kansas	427-453	4	2.15	22.5	21.3	22.0				8		1
<u>Chanute Shale</u>	Pennsylvanian	Montgomery County, Kansas	152-297	4	2.51	9.1	10.6	7.3				8		1

¹Total porosity.

REGION III

REFERENCES

1. Athy, F. L., 1930, Density, Porosity, and Compaction of Sedimentary Rocks: Bull. Am. Assoc. Pet. Geol., v. 14, pp. 1-24.
2. Berg, R. R., 1975, Capillary Pressure in Stratigraphic Traps: Am. Assoc. Pet. Geol. Bull., v. 59, p. 939-956.
3. Birch, F.; Schairer, J. F., and Spicer, C. H., 1942, Handbook of Physical Constants: Geological Society of America, Special Paper No. 36, 325 p.
4. Gondouin, M., and Scala, C., 1958, Streaming Potential and the SP Log: Trans. A.I.M.E., v. 213, p. 170-179.
5. Hedberg, H. D., 1926, The Effect of Gravitational Compaction on the Structure of Sedimentary Rocks: Bull. Am. Assoc. Pet. Geol., v. 10, pp. 1035-1072.
6. Jennings, A. R., and Schroeder, M. C., 1968, Laboratory Evaluation of Selected Radioisotopes as Ground-Water Tracers: Water Resources Research, v. 4, no. 4, pp. 829-838.
7. Katz, D. L., 1942, Possibilities of Secondary Recovery for the Oklahoma City Wilcox Sand: Trans. A.I.M.E., v. 146, p. 28-53.
8. Manger, E. G., 1963, Porosity and Bulk Density of Sedimentary Rocks: U. S. Geological Survey Bulletin 1144-E, 55 p.
9. Morris, R. C.; Proctor, K. E., and Koch, M. R., 1977, Petrology and Diagenesis of Deep-Water Sandstones, Ouachita Mountains, Arkansas and Oklahoma Abstr: A.A.P.G. Bull., v. 61, p. 1384.
10. Rieke, Herman H. III, and Chilingarion, George V., 1974, Compaction of Argillaceous Sediments: Developments in Sedimentology, v. 16, 424 p.
11. Schenck, K. D., An Investigation of the Streaming Potential Developed in Formations of low Permeability, M.S. Thesis, University of Oklahoma, 1955.
12. Wilkinson, W. M., 1953, Fracturing in Sprayberry Reservoir, West Texas: Bull. Am. Assoc. Pet. Geol., v. 37, p. 250-265.

REGION 4: THE GULF COAST AND THE MISSISSIPPI EMBAYMENT

The southeastern coast of the United States is characterized by a Paleozoic episode of plate convergence following by a history of diverging plates which began with the Triassic and is continuing today.

With the end of the Paleozoic, ancestral North America and Europe collided with Gondwanaland (Seyfert and Sirkin, 1973) after closing of the Theic Ocean. This collision resulted in the formation of the Appalachian belt and its southern extension into the Gulf Coast area, the Marathon-Ouachita Mountains. After a brief continental episode (Permian) during which evaporites were formed, subsidence and deposition of a clastic wedge began to take place in response to the opening of the Atlantic Ocean. Most clastic sediments are Mesozoic and Cenozoic, and the shales are regarded as the likely source of the Gulf Coast oil and gas fields (many were formed by salt dome tectonics). Although most shales are Tertiary and Cretaceous, Paleozoic units, more representative of Appalachian and Mid Continent regions occasionally crop out around the periphery of the basin or in domal uplifts. Figure 13 shows typical relationships of this region.

Figure 13: Section across the Gulf Coast clastic wedge (After Murray, 1961).
 Kc: Coahuila Series; Kcm: Comanche Series; Kg: Gulf Series;
 Em: Midway Stage; Es: Sabine Stage; Ec: Clairborne Stage;
 Ej: Jackson Stage; φv: Vicksburg Stage; φf: Frio Formation;
 φa: Anahvac Form; TmQp-Mio-Plio-Pleistocene.

TABLE 4-4 SUMMARY OF ROCK UNITS IN THE GULF COAST AND MISSISSIPPI EMBAYMENT REGION
[From Murray (1961)]

NOTE: Units described in the hydrologic tables are predated by *.

Age	Stratigraphic Unit	Thickness (M)	Description	
MIO-PLIOCENE UNITS		600-1000	Marine clastics	
OLIGOCENE	* Anahuac Formation	300	Dark green shales and sandstones	
	* Hackberry-Frio Formations	1,000-2,500	Sandstones interbedded with subordinate shale	
	Vicksburg Stage	200	Limestone grading into clastics	
EOCENE	Jackson Stage	300-1,000	Shale sequence with minor limestone	
	<u>Claiborne Stage</u>	1,000	Limestone with minor chert, gypsum, shale and sandstone	
	Yegua Formation	}		
	Cook Mtn. Formation			
	Mt. Selman Formation			
	<u>Sabine Stage</u>	1,500	Sandstone, shale, with minor coal	
	Wilcox Group			
Midway Stage	400	Calcareous sandstone, siltstone, claystone, minor chalk		
CRETACEOUS	Upper	<u>Gulf Series</u>	Sandstone, glauconitic sandstone, shale, chalk, marl, limestone, coal	
		Navarra Stage		}
		Taylor Stage		
		Austin Stage		
		Eagle Ford Stage		
	Middle and Lower	<u>Comanche Series</u>	Limestone, shale, sandstone, minor anhydrite	
		Washita Stage		}
		Fredericksburg Stage		
		Trinity Stage		

TABLE 4-4 (Continued)

Age		Stratigraphic Unit	Thickness (M)	Description
CRETACEOUS	Lower	Coahuila Series	300-1,000	Limestone and shale, with sandstone
JURASSIC	Upper	Sabinas Series	800	Red conglomerate and sandstone, limestone, shale, anhydrite
-----Unconformity-----				
PALEOZOIC	Basement	Includes:		
		* Cherokee Shale (Pennsylvanian)		
		* Flint Clay (Pennsylvanian)		
		* Hamilton Shale (Devonian)		
		[See Table 3-3 for descriptions.]		

Hydrologic Data

REGION IV

GULF COAST AND MISSISSIPPI EMBAIMENT

Geological Setting	Age	Locality	Depth (ft)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
						Av.	Max.	Min.	Av.	Max.	Min.			
<u>Anahuac and Frio Formations</u>	Oligocene	Pan American #5, farmers and land canal well, Manchester Field, Louisiana	1006	no data		20			1.8x10 ⁻⁷			17	Porosities computed from rock density by the use of a plot relating rock porosity and bulk density	
			1524			18			2.6x10 ⁻⁷					
			1981			16			4.1x10 ⁻⁹					
			2430			14			7x10 ⁻¹⁰					
			2896			12			1x10 ⁻¹⁰					
			3048			12			1x10 ⁻¹⁰					
			2079			14			7x10 ⁻¹⁰					
			3139			16			4.1x10 ⁻⁹					
			3566			16			4.1x10 ⁻⁹					
<u>Shales</u>	Cenozoic?	Gulf Coast, Texas and Louisiana	0		1.35	50						4.5	Laboratory measurement	a
			610		2.03	25			2x10 ⁻⁵					

^aTypical well parameters.

REGION IV (continued)

Geological Setting	Age	Locality	Depth (M)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
						Av.	Max.	Min.	Av.	Max.	Min.			
[Shales]	Cenozoic and Cretaceous	Gulf Coast, Texas and Louisiana	1220		2.11	22						4,5		
			1810		2.19	19								
			2441		2.27	16								
			3049		2.35	13								
			3659		2.43	10								
			4269		2.43	10								
			4878		2.46	9								
			5480		2.46	9								
			6098		2.48	8								

REGION IV (continued)

Geological Setting	Age	Locality	Depth (ft)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/g)			Ref.	Determination Method	Notes
						Av.	Max.	Min.	Av.	Max.	Min.			
<u>Shale</u>	Upper Cretaceous	Houston County, Texas				10.1						8	Direct measurement with a gas porosimeter and measurement of grain volume.	
<u>Shales</u>	Upper Cretaceous (7)	East Texas	1128	[10.6]*	2.40	14.5						10	(see above)	
			3336	[1.22]*	2.30	27.5								b
<u>Anomilina bilaterata Zone</u>	Upper Cretaceous (7)	Martin Ranch, Texas				15	10		8.6×10^{-6}			2	**	
<u>Upper Black Underclay</u>	Pennsylvanian	New Brazil, Indiana	Trench	1		19.1						13		c

^b Shale resistivity at 25°C and effective stress of 1000 psi.

*Total porosity.

*Resistivity (ohm m) S.C.

** Shale-sandstone cycle
Shales - Topset
Delta Front Shale-Sand
Prodelta Shale - Base
Chocolate Bayou Field

REGION IV (continued)

Geological Setting	Age	Locality	Depth (M)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
						Av.	Max.	Min.	Av.	Max.	Min.			
<u>Consolidated Sandy Shale</u>	-	South Texas	2513-2514	3		21			5.1x10 ⁻⁵			1	Electrical resistivity data	d
<u>Shale</u>	Pennsylvanian	Centralla Field, Illinois	425			14.2			(1) -	(2) 1.7x10 ⁻¹²	(3) 8.6x10 ⁻¹²	8	Streaming potential and SP log	e
		Colorado County, Texas	2761			7.4			2.6x10 ⁻¹⁰	3.4x10 ⁻¹²	-			
		Houston County, Texas	7						8.6x10 ⁻¹³	6x10 ⁻¹²	-			
		Clark County, Illinois	143						7.7x10 ⁻¹¹	-	-			
<u>Cherokee Shale</u>	Pennsylvanian	Fulton, Missouri	Outcrop	2	2.29	17.1	17.2	17.0				9	Heicher Method	

^d Formation resistivity factor = 14.

- ^e (1) 0.02N NaCl
(2) 0.2N NaCl
(3) 1N NaCl

REGION IV (continued)

Geological Setting	Age	Locality	Depth (ft)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
						Avg.	Max.	Min.	Avg.	Max.	Min.			
<u>Flint Clay</u>	Pennsylvanian	Fulton, Missouri	Outcrop	2	2.37	10.1			1.7×10^{-11}			13		f
<u>Shale</u>	Pennsylvanian	Union County, Kentucky										7		g
Core 3807														
#1			9.6	1		8								
#2			52.3	1		3.7								
#3			64.6	1		15.2								
Core 3733														
#1			27.0	1		8.9								
#2			29.8	1		6.4								
#3			52.7	1		6.0								
#4			76.3	1		5.8								
#5			76.4	1		5.4								
#6			76.6	1		5.8								

f = total porosity

g Samples taken from two wire test holes drilled by the Peabody Coal Company. Core 3807 starts at 300 ft. stratigraphically higher than Core 3733. Porosity decreases with increasing depth of burial, negative correlation strongly influenced by illite content and clay mineral orientation. Porosity decreases with an increase in preferred clay mineral orientation and an increase in illite content.

REGION IV (continued)

Geological Setting	Age	Locality	Depth (ft)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
						Avg.	Max.	Min.	Avg.	Max.	Min.			
[Shale]	Pennsylvanian	Union County, Kentucky	-	-	-	-	-	-	-	-	-	7		
Core 3733														
#23			402.3	1		7.1								
#24			429.5	1		3.3								
#25			452.2	1		3.6								
<u>Shale</u>	?	South Pass, Louisiana	1370-4270	many		15-20						15		
<u>Shale</u>	?	Pan American Farmers A-1 Well, Manchaster Field, Louisiana	2460-3345	17	1.85-2.04	13.1-17.8						15		h
			3345-3960	11	2.07-2.16	17.6-19.5								
<u>Shale</u>	?	Gulf Coast	3350-5490			18-20						15		i

^h Porosity and density ranges

ⁱ Porosity measured in lab using shale chips.

REGION IV (continued)

Geological Setting	Age	Locality	Depth (M)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
						Av.	Max.	Min.	Av.	Max.	Min.			
[Shale]	Pennsylvanian	Union County, Kentucky										7		
Core 3733														
#7			77.0	1		7.1								
#8			77.3	1		5.0								
#9			77.3	1		5.4								
#10			77.5	1		4.0								
#11			88.2	1		3.6								
#12			110.7	1		4.3								
#13			113.8	1		5.3								
#14			155.9	1		6.0								
#15			164.3	1		6.1								
#16			211.1	1		6.1								
#17			236.7	1		5.8								
#20			341.4	1		10.1								
#21			349.3	1		5.8								
#22			386.3	1		4.5								

REGION IV (continued)

Geological Setting	Age	Locality	Depth (ft)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
						Av.	Max.	Min.	Av.	Max.	Min.			
<u>Shale</u>	?	Texas Gulf Coast	3510			20						15		
<u>Shale</u>	?	Louisiana Gulf Coast	3190-5400	71		10.8-22.5						15		
<u>Shale</u>	?	Gulf Coast	121-3688	55		7.5-45						11		
			579-4267	23		11-34								
<u>Shale</u>	?	Texas							6×10^{-12}			16	Lab.	j
<u>Shale</u>	?	Gulf Coast				3			7.7×10^{-14}			10	Lab.	
						3			1.3×10^{-14}			10	Lab.	
						-			8.58×10^{-15}			16	Lab.	
						-			2.1×10^{-15}			16	Lab.	k

j 0.2N NaCl solution used as permeant.

k 10,000 psi load.

REGION IV (continued)

Geological Setting	Age	Locality	Depth (ft)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
						Av.	Max.	Min.	Av.	Max.	Min.			
[Shale]	?	Gulf Coast	-	-	-	3			3.9×10^{-9}			1 ¹	Lab.	
			1216-4257			14-20			1.7×10^{-10}	to 1.8×10^{-10}		12	Lab.	1
<u>Greenish Shale</u>	?	Shreveport, Louisiana			dry 2.10 sat 2.33	22.6						3, 14		m
<u>Reddish Shale</u>	?	Shreveport, Louisiana			dry 2.22 sat 2.42	20.0						3, 14		n
<u>Shale</u>	?	Shreveport, Louisiana			dry 2.29 sat 2.46	16.9						3, 14		w
<u>Shale</u>	?	Batesville, Arkansas			dry 2.05 sat 2.86	1.5						3		

¹ Estimates from graph for under-compacted shale.

^m Just above pay sand of Curtis l.

^w Deep gas sand of Morges Ward l.

REGION IV

OTHER PROPERTIES: SHALE RESISTIVITY DATA

Southwest Louisiana (Ref. 6)			
(S-TWP-R)			
Well Location	Shale Zone	Depth (M)	Sh. Res. at Spl. Depth (ohm-M)
73-105-04E	Bolivina-Mex	4660-4664	0.77
21-105-03E	U. Camerina	3643-3645	0.59
20-105-03E	L. Camerina	3625-3627	0.62
17-105-03E	Bolivina-Mex	4060-4063	0.38
08-105-03E	Discorbis	3047-3049	1.10
31-075-04E	U. Nodosaria	3045-3048	1.02
20-075-03E	Dalgle	2949-2954	0.83
76-075-03E	U. Nodosaria	3064-3069	0.97
01-085-02E	Struma	3318-3321	0.90
09-095-03E	Klump-D	3661-3665	0.60
04-095-03E	Frio	2927-2929	0.84
09-095-03E	Frio	4037-4040	0.94
11-105-02E	U. Texana	3529-3531	0.35
83-085-03E	Frio	4389-4392	0.30
14-115-02E	Mary Nowei	3765-3767	0.38
47-095-02E	Klump-E	3496-3501	0.83
36-085-02E	Nodosaria	3886-3891	0.95
02-115-02E	Mary Tex	3734-3737	0.65
01-115-02E	Maryulina	3744-3746	0.57

REGION IV

REFERENCES

1. Archie, C. E., 1947, Electrical Resistivity and its Interpretation: Amer. Assoc. Pet. Geol. Bull., v. 31, p. 350-366.
2. Bedoult, D. G., and Gregory, A. R., 1977, Texas Geothermal Project Slated to Begin Operations at Martin Ranch: Oil & Gas Journal, v. 75, no. 41, p. 184-187.
3. Birch, F.; Schairer, J. F., and Spicer, C. H., 1942, Handbook of Physical Constants: Geological Society of America, Special Paper No. 36, 325 p.
4. Bradley, J. S., 1975, Abnormal Formation Pressure: Amer. Assoc. Pet. Geol. Bull., v. 59, p. 957-973.
5. Dickey, P. A., 1976, Abnormal Formation Pressure: Discussion: Amer. Assoc. Pet. Geol., v. 60, p. 1124-1128.
6. Dickey, P. A.; Collins, A. G., and Fajardo, I., 1972, Chemical Composition of Deep Formation Waters in Southwestern Louisiana: A.A.P.G. Bull., v. 56, p. 1530-1533.
7. Gipson, Mack, J., 1966, A Study of the Relations of Depth, Porosity, and Clay Mineral Orientation in Pennsylvanian Shales: Jour. of Sedimentary Petrology, v. 36, no. 4, pp. 888-903.
8. Gondouin, M., and Scala, C., 1958, Streaming Potential and the SP Log: Trans. A.I.M.E., v. 213, p. 170-179.
9. Hedberg, H. D., 1926, The Effect of Gravitational Compaction on the Structure of Sedimentary Rocks: Bull. Am. Assoc. Pet. Geol., v. 10, pp. 1035-1072.
10. Hubbert, M. K. and Rubey, W. W., 1959, Role of Fluid Pressure in Mechanics of Overthrust Faulting, II. Overthrust Belt in Geosynclinal Area of Western Wyoming in Light of Fluid-Pressure Hypothesis: Geological Society of America Bulletin, v. 70, no. 2, pp. 167-206.

REGION IV: REFERENCES (continued)

11. Magara, K., 1971, Permeability Considerations in Generation of Abnormal Pressures: Society of Petroleum Engineers Journal, v. 11, pp. 236-242.
12. Magara, K., 1974, Compaction, Ion Filtration, and Osmosis in Shale and Their Significance in Primary Migration: Amer. Assoc. of Petroleum Geologists Bulletin, v. 58, no. 2, pp. 283-290.
13. Manger, E. G., 1963, Porosity and Bulk Density of Sedimentary Rocks: U. S. Geological Survey Bulletin 1144-E, 55 p.
14. Melcher, A. F., 1921, Determination of Pore Space of Oil and Gas Sands: Trans. Am. Inst. Min. Eng., v. 65, pp. 480-489.
15. Price, L. C., 1976, Aqueous Solubility of Petroleum as Applied to its Origin and Primary Migration: American Association of Petroleum Geologists Bulletin, v. 60, no. 2, pp. 213-244.
16. Rieke, Herman I. III, and Chilingarion, George V., 1974, Compaction of Argillaceous Sediments: Developments in Sedimentology, v. 16, 424 p.
17. Schmidt, G. W., 1973, Interstitial Water Composition and Geochemistry of Deep Gulf Coast Shales and Sandstones: Am. Assoc. Pet. Geol. Bull., v. 57, pp. 321-337.
18. Waxman, M. H., and Thomas, E. C., 1975, Electrical Conductivities of Shaly Sands - I. The Relation Between Hydrocarbon Saturation and Resistivity Index: II. The Temperature Coefficient of Electrical Conductivity: A.I.M.E. Trans., v. 257, p. 213-225.

REGION 5: THE APPALACHIAN MOUNTAINS AND THE GREAT LAKES

The north and eastern portion of the United States has evolved, much like the Gulf Coast, along two opposing trends. During the Paleozoic, the geologic history has been characterized by collisions of plates, disappearance of proto-oceans, and building of one supercontinent (Pangea). In Late Devonian time, the northern Appalachians (New England) were formed as the Iapetus Ocean disappeared (Mintz, 1977). In Late Carboniferous time the southern Appalachian-Ouachita range formed a weld between Laurasia and Gondwanaland (closing the Theic Ocean), but this union was short lived: with the advent of the Triassic the two continents began to part their ways as the Atlantic Ocean started to grow.

Record of these geologic events has been preserved in the form of Upper Precambrian and Paleozoic remnants of oceanic basins folded into Appalachian structures and of Triassic red beds (Newark Series) occupying graben-like basins. The following shales are found within this geologic record:

- Late Precambrian (Nonsuch shale), Late Ordovician (Martinsburg shale), and Devonian Mississippian (Chattanooga shales), all three characterize the early compressive tectonic style. Their relationship is illustrated in Fig. 14.

- Triassic (Brunswick shale) is more representative of a setting found in the Atlantic Plains, which are discussed in the next region.

Figure 14: Stratigraphic diagram showing the relationships between the Martinsburg and Chattanooga shales in the Appalachian, Great Lakes Region (After Eardley, 1962)

TABLE 4-5 SUMMARY OF ROCK UNITS OF THE APPALACHIAN AND GREAT LAKES REGION
[From Schuchert (1943)]

NOTE: Units described in the hydrologic tables are preceded by *.

Age		Stratigraphic Unit	Thickness (M)	Description
LOWER PERMIAN AND UPPER PENNSYLVANIAN		Cassaville and Washington Formations	0-366	Brown and red sandstone, shale, thin limestone and unimportant coals
PENNSYLVANIAN	Upper	* Monongahela Formation	79-91	Shale, limestone, sandstone, and coals
	Middle	Conemaugh Formation	122-244	Red shale, massive pebbly sandstone, with coals and fire clays
		* Allegheny Formation (Flint Clay?)	85-122	Sandstone, shale, limestone, coals, fire clays
	Lower	Pottsville Group	91-1,265	Sandstone, shale, coals
-----Disconformity-----				
MISSISSIPPIAN	Upper	Mauch Chunk Formation	91-1,052	Green sandstone, interbedded with red and green shale
				-----Disconformity-----
		Greenbrier Formation	247-549	Fossiliferous limestone, with red and green shale
				-----Disconformity-----
	Middle	Maccrady Group	7-107	Red, purple and yellow shale, earthy limestone, and calcereous sandstone
	Lower	Pocono Formation	213-668	Gray or red sandstone, sandy shale, unimportant coal

TABLE 4-5 (Continued)

Age		Stratigraphic Unit	Thickness (M)	Description	
DEVONIAN	Upper	Hampshire Formation (partly correlative with the Chagrin Shale* and Chattanooga Shale*)	945-1,143	Red and green shale, sandstone	
		Chemung Formation	518-1,067	Shale, sandstone, thin coals and underclay	
		Portage Formation	518-610	Shale and sandstone	
		Gensee Formation	15-91	Shale	
	-----Disconformity-----				
	Middle	* Hamilton and Marcellus Formations	488 (max.)	Shale	
	Lower	Ridgeley Formation	15-84	Sandstone	
		Shriver Formation	0-56	Cherty limestone	
		-----Disconformity-----			
		New Scotland Formation	4-20	Limestone and calcereous sandstone	
		Coeymans Limestone	3-30	Massive crinoidal limestone	
-----Disconformity-----					
SILURIAN	Upper	Keyser Limestone	56	Limestone with local shale, and sandstone	
		-----Disconformity-----			
		Tonoloway Formation	168	Argillaceous limestone, calcareous shale, sandstone at base	
		Wills Creek Formation	0-183	Calcareous shale, argillaceous limestone, some sandstone	
-----Disconformity-----					

139

TABLE 4-5 (Continued)

Age		Stratigraphic Unit	Thickness (M)	Description
SILURIAN	Middle	McKenzie Formation	15-122	Shale, argillaceous limestone, some sandstone
		Clinton Formation	122-183	Shale, sandstone, and limestone
	Lower	Tuscorora Formation	15-94	Massive sandstone
-----Disconformity-----				
ORDOVICIAN	Upper	Juanita Formation	122-335	Sandstone
	Middle to Upper	* Martinsburg Formation	610-1,067	Shale, sandstone, and limestone
	Middle	Chambersburg Formation	146-175	Limestone with shale partings
		Stones River Group	113-223	Limestone
	Lower	Beekmantown Formation	610-762	Dolomite
-----Disconformity-----				
CAMBRIAN	Upper	Conococheague Formation	488-549	Magnesian limestone
	-----Disconformity-----			
	Middle	Elbrook Limestone	427-762	Limestone, shaly limestone, shale
	Lower	Waynesboro Formation	488	Magnesian limestone, calcareous sandstone, red or purple siliceous shale
-----Unconformity-----				

TABLE 4-5 (Continued)

Age		Stratigraphic Unit	Thickness (M)	Description
CAMBRIAN	Lower	Tomstown Formation	111-319	Dolomite, marble, limestone and shale
		Antietam Formation	152	Quartzite, sandstone
		Harpers Formation	366	Slate, quartzite
		Weverton Formation	152-183	Quartzite, conglomerate
-----Unconformity-----				
PRECAMBRIAN	Uppermost	Keweenawan	16,500-12,200	Lava flows, red sandstone and shales
		(Includes Nonesuch Formation)	100	Black shale
-----Unconformity-----				
PROTEROZOIC AND EARLIER				

HYDROLOGIC DATA

REGION V
GREAT LAKES AND APPALACHIANS

Geological Setting	Age	Locality	Depth (ft)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
						Avg.	Max.	Min.	Avg.	Max.	Min.			
<u>Blue-Gray Shale overlying Keener Sand</u>	Mississippian	Jerusalem, Ohio	440	dry	2.46									
				sat	2.56	9.7						1,3		
		Miltonburg, Ohio	450	dry	2.41									
				sat	2.52	11.0						1,3		
<u>Black Shale</u>	Devonian	Floyd County, Kentucky	669	dry	2.41									
				sat	2.41	0.0						1		

REGION V (continued)

Geological Setting	Age	Locality	Depth (ft)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
						Av.	Max.	Min.	Av.	Max.	Min.			
<u>Allegheny Formation</u> (Shale and Slate)	Pennsylvanian	Bakerton, Pennsylvania	≈152	2	2.72	1.7						2		c
<u>Monongahela Formation</u>	Pennsylvanian	Scotts Run, West Virginia	Mine	5	2.5	6.1						2		d
<u>Martinsburg Shale</u> (Slate)	Ordovician	Bangor, Pennsylvania	Quarry		2.74	1.0						2		c
<u>Monesuch Shale</u> (Siliceous)	Pre-Cambrian	White Pine, Michigan	Mine	6	2.76	1.6	1.7	1.5				2		a

^c Effective porosity.

^d Effective porosity. Compressive strength 11,600 lb/in².

REGION V

Geological Setting	Age	Locality	Depth (ft)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
						Av.	Max.	Min.	Av.	Max.	Min.			
<u>Went Falls Formation</u> (Chagrín Shale)	Upper Devonian	Lincoln County, West Virginia				2.5						4	From 230 matrix and bulk density measurement.	a
<u>Chattanooga Shale</u>	Devonian and Mississippian	Irving Field, Kentucky	sub-surface	2	2.38	7.5	7.6	7.4				2		b
		Near Smithville, Tennessee	Mine	2	2.53	1.7	1.7	1.76				2		c

^a1250 ft. core, overall average.

^bTotal porosity.

^cEffective porosity.

REGION V
OTHER PROPERTIES

Formation	Age	Locality	Resistivity (ohm-cm)	Reference
<u>Nonesuch Shale</u> (Siliceous)	Pre- Cambrian	White Pine, Michigan	10^4	1
<u>Shale</u>	?	Shamokin, Pennsylvania	10^5	1

REGION V

REFERENCES

1. Birch, F.; Schairer, J. R., and Spicer, C. H., 1942, Handbook of Physical Constants: Geological Society of America, Special Paper No. 36, 325 p.
2. Manger, E. G., 1963, Porosity and Bulk Density of Sedimentary Rocks: U. S. Geological Survey Bulletin 1144-E, 55 p.
3. Melcher, A. F., 1921, Determination of Pore Space of Oil and Gas Sands: Trans. Am. Inst. Min. Eng., v. 65, pp. 480-489.
4. Nuhfer, E. G., and Vinopal, R. J., 1978, Nature of Porosity in Upper Devonian Shales of Lincoln County, West Virginia: Geol. Soc. Amer. Abst. Programs, v. 10, no. 7, p. 464.

REGION 6: THE ATLANTIC COASTAL PLAIN AND THE TRIASSIC BASIN

The east coast of the United States is a transitional zone between the Appalachian region and the Atlantic Ocean. Its geology contains a record of Mesozoic sea-floor spreading and also presents some analogies with the Gulf Coast. Early stages of spreading are indicated by the Triassic Basins of the Appalachians (which contain Brunswick shale) and later stages are found along the Coastal Plains to the east. A Cretaceous shale (Middendorf) is found in this second zone.

Structural relationships between the various units are shown in Figs. 15 and 16.

Figure 15: Generalized structural sections across the Appalachians and the Atlantic Coastal Plain (From Mintz, 1977)

Figure 16: Section showing detailed structure of a Triassic Basic (From Eardley, 1962)

TABLE 4-6 GENERALIZED STRATIGRAPHIC COLUMN FOR NEW JERSEY (ATLANTIC COASTAL PLAIN)
[From Schuchert (1943)]

NOTE: Units described in the hydrologic tables are preceded by *.

Age		Stratigraphic Unit	Thickness (M)	Description
PLIOCENE (?) - PLEISTOCENE		Beacon Hill Formation	0-15	Gravel - occurs as isolated remnants (terrace gravels) [Archie, 1947]
-----Disconformity-----				
MIOCENE	Upper (?)	* Cohansey Sand	15-137	Quartz sand and lenses of clay and gravel
	Middle	* Kirkwood Formation	2-30	Banded micaceous quartz sands, lignitic clays and clay at base
-----Disconformity-----				
EOCENE	Middle	Shark River Formation	3	Glauconitic sand and clay
	Lower	Manasquan Formation	9-27	Nearly pure greensand marl
		Vincentown Formation	30	Yellow quartz sand facies grading into lime-sand to the southwest
		Hornerstown Formation	0-9	Dark, sparsely fossiliferous, nearly pure greensand marl
-----Disconformity-----				
CRETACEOUS	Upper	Tinton-Redbank Formations	4-37	Tinton - glauconitic red sand Redbank - very ferruginous red sand
		Mount Laurel-Navesink Formations	3-21	Mount Laurel - fossiliferous quartz sand with some glauconite Navesink - nearly pure greensand marl

TABLE 4-6 (Continued)

Age	Stratigraphic Unit	Thickness (M)	Description
CRETACEOUS	Upper		
	Wenonah-Marshalltown Formations	15-43	Wenonah - black to reddish brown sand sometimes strongly micaceous, with small amounts of glauconite Marshalltown - sandy clay to clayey greensand and marl, or laminated micaceous clay or pure greensand marl
	Englishtown Sand	0-30	Quartz sand
	Woodbury Clay	15	Black, somewhat micaceous and slightly sandy clay
	Merchantville Clay Marl	11-18	Black, glauconitic, somewhat sandy clay marl
	* Magothy Formation (Middendorf Formation - South Carolina)	3-53 30-60	Magothy - clay, white sand, with seams of black lignite and thin beds of black clay Middendorf - Partly correlative with Magothy in New Jersey. Dark laminated clay and micaceous sand. [Archie, 1947]
	Raritan Formation	46-152	Variable and variegated sands and plastic clays
-----Unconformity-----			
TRIASSIC	Upper		
	NEWARK GROUP		
	* Brunswick Shale	1,524-3,658	Red shale and sandstone
	Watchung Basalt	91-366	Basalt flows
	Locketong Formation	518-1,097	Black shale, dark argillite, flagstone, and rare thin limestone
	Stockton Formation	701-945	Arkosic sandstone, conglomerate and red shale (lies on Precambrian)
-----Unconformity-----			
PALEOZOIC BASEMENT [See Table 3-5.]			

HYDROLOGIC DATA
REGION VI
ATLANTIC PLAIN AND TRIASSIC BASINS

Geological Setting	Age	Locality	Depth (ft)	# of Samples	Dens- sity (gm/ cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
						Av.	Max.	Min.	Av.	Max.	Min.			
<u>Blue Clay</u>	Miocene	Salisbury, Maryland				Consolidation Load (Kj/cm ²)			From Consolidation		Constant Flow	3	Lab.	
			23.7	1		4			5.3x10 ⁻⁷		5.8x10 ⁻⁷			a
						8			1.5x10 ⁻⁷		8.7x10 ⁻⁸			
			23.6	1		4			4.2x10 ⁻⁷		1.3x10 ⁻⁷			b
						8			2.7x10 ⁻²		5.5x10 ⁻⁸			
			24.4	1		4			6.4x10 ⁻⁷		2.2x10 ⁻⁶			c
						8			1.5x10 ⁻⁷		5x10 ⁻⁷			
			24.1	1		4			1.9x10 ⁻⁷		9.1x10 ⁻⁷			d
						8			1.5x10 ⁻⁷		5.5x10 ⁻⁷			
			23.1	1		4			2.5x10 ⁻⁷		1.5x10 ⁻⁸			e
						8			6x10 ⁻⁸		1x10 ⁻⁸			
			24.7	1		4			1.0x10 ⁻⁷		1.1x10 ⁻⁷			f
						8			1.4x10 ⁻⁷		4.2x10 ⁻⁸			
			25	1		4			1.4x10 ⁻⁷		4.2x10 ⁻⁸			g
						8			3.0x10 ⁻⁸		1.8x10 ⁻⁸			

^a Sample C-2.

^b Sample C-11.

^c Sample C-7.

^d Sample C-12.

^e Sample C-8.

^f Sample C-14.

^g Sample C-9.

REGION VI (continued)

Geological Setting	Age	Locality	Depth (ft)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Ref.	Determination Method	Notes
						Av.	Max.	Min.	Av.	Max.	Min.			
<u>Kirkwood Formation</u>	Miocene	Yorktown, New Jersey												
Yellow Clay			1.2	1	1.3	51.9							1	Permeability computed from Theis nonequilibrium equation. Permeability computed using the relation $T=Kb$ where b = thickness. $T_{min} = 6000$ ft. $T_{max} = 16,000$ ft.)
Yellowish Clay			3	1	1.62	40.3								
Blue Clay			4	1	1.70	38.6								
<u>Cohansey Sand (Clay)</u>	Miocene-Pliocene (2)	Crossley, New Jersey	out-crop	2	1.67	37.0	37.4	36.6				2		b
<u>Brunswick Formation (Shale)</u>	Late Triassic to Early Jurassic	Flemington, New Jersey	no data	no data								4		c
Observation Well #1	} Perpendicular to strike								3.7×10^{-4}	6.9×10^{-4}	2.6×10^{-4}			
Observation Well #2									3.2×10^{-4}	5.9×10^{-4}	2.2×10^{-4}			
Observation Well #3	} Perpendicular to strike								2.5×10^{-4}	4.5×10^{-4}	1.7×10^{-4}			
Observation Well #4									2.5×10^{-4}	4.5×10^{-4}	1.7×10^{-4}			

1 Soft, hematite stained red shales with some interbedded sandstone. Strike N51°E, dip 25°NW. Alignment of major fracture system is parallel to strike. Sedimentation basin, block faulted and rotated to present position. Fracture porosity.

b Total porosity.

REGION VI (Continued)

Geological Setting	Age	Locality	Depth (ft)	# of Samples	Density (gm/cm ³)	Porosity			Hydraulic Conductivity (cm/s)			Cat.	Determination Method	Notes
						Av.	Max.	Min.	Av.	Max.	Min.			
<u>Middendorf Formation</u> (White Clay)	Cretaceous	Aiken and Richland Counties, South Carolina	out-crop	2	1.55	40.7	42.3	39				1		h
<u>Claystone</u>	Triassic	Savannah River Plant, South Carolina	400						2.9×10^{-10}			2	Calculated from well yield data	j
			388						3.9×10^{-12}					k
<u>Mudstone</u>	Triassic	Savannah River Plant, South Carolina	1282	several		3.3			1.16×10^{-10} to 1.16×10^{-11}			2		l
<u>Mudstone (Massive)</u>	Triassic	Savannah River Plant, South Carolina	1010	several					1.7×10^{-9}			2		m

h Total porosity.

j Well P5R.

k Well P12R.

l Well DRB-10. Effective porosity 0.53%.

m Well DRB-11.

REGION VI
OTHER PROPERTIES

	Consolidation Load (Kg/cm ²)	Diffusivity (cm ² /sec)	Determination Method	Reference
<u>Blue Clay - Miocene,</u> <u>Salisbury, Maryland</u>	4	2.3×10^{-2}		
Sample C-2	8	1.7×10^{-2}		
Sample C-7	4	1.3×10^{-2}		
	8	1.9×10^{-2}		
Sample C-8	4	2.9×10^{-2}		
	8	2.5×10^{-2}		
Sample C-9	4	2.3×10^{-2}	Lab	3
	8	2.0×10^{-2}		
Sample C-11	4	1.4×10^{-2}		
	8	5.3×10^{-3}		
Sample C-12	4	2.0×10^{-2}		
	8	1.8×10^{-2}		
Sample C-14	4	5.0×10^{-3}		
	8	1.8×10^{-3}		

REGION VI

REFERENCES

1. Manger, E. G., 1963, Porosity and Bulk Density of Sedimentary Rocks: U. S. Geological Survey Bulletin 1144-E, 55 p.
2. Marine, I. Wendell, 1963, Geohydrology of Buried Triassic Basin at Savannah River Plant, South Carolina: in Underground Waste Management and Artificial Recharge, 2nd International Symposium, New Orleans, La., American Association of Petroleum Geologists, v. 1, pp. 481-504.
3. Wolf, R. G., 1970, Field and Laboratory Determination of the Hydraulic Diffusivity of a Confining Bed: Water Resources Research, v. 6, no. 1, pp. 194-203.
4. Vecchiolli, J., 1967, Directional Hydrolic Behavior of a Fractured Shale Aquifer in New Jersey, In Hydrology of Fractured Rocks: Assoc. Int. D'Hyd. Sci., v. 1, p. 318-326.

BIBLIOGRAPHIC REFERENCES

American Geological Institute, 1972, Glossary of Geology, Gary, M., McAfee, R., Wolf, C.L., edit., Washington, D.C.

Archie, G. E., 1950, Introduction to petrophysics of reservoir rocks: Am. Assoc. Petrol. Geol., Bull. V 34, n. 5, p. 943-961.

Aronson, J. L., & Hower, J., 1976, Mechanism of burial metamorphism of argillaceous sediments: 2 Radiogenic Argon Evidence; Geol. Soc. of Am., Bull. V. 87, p. 738-744.

Atwater, J., 1970, Implication of plate tectonics for the Cenozoic tectonic evolution of western North America, Geol. Soc. of Am., Bull. 81, p. 3513-3536.

Berry, Fred A. F., 1959, Hydrodynamics and geochemistry of the Jurassic Cretaceous systems in the San Juan Basin, Northwestern New Mexico and Southwest Colorado, Ph.D. thesis, Stanford Univ.

Clark, T. H. & Stearn, C. W., 1968, Geological Evolution of North America, 2nd Ed., Ronald Press Co. Publ.

Cummings, J. C., Touring, R. M., & Brabb, E. E., 1962, Geology of the northern Santa Cruz Mountains; Calif. Div. of Mines and Geol., Bull. 181, p. 179-220.

Dickinson, W. R., 1971, Plate tectonic models for orogeny at continental margins, Nature, V. 232, p. 41-42.

du Rouchet, 1978, A tentative geomechanical theory of oil migration, Bull. Cent. Rech., Explor., Prod. ELF Aquitaine, Vol. 2, n. 2, p. 337-373.

Eardley, A. J., 1962, Structural geology of North America, Harper and Row Publ., New York, N.Y., 743 p.

Gill, J. R., Merriwether, E. A., and Cobban, W. A., 1970, Stratigraphy and nomenclature of some Upper Cretaceous and Lower Tertiary rocks in South Central Wyoming, U. S. Geol. Surv. Prof. Pap. 667, 53 p.

Golder Associates, 1977, Development of site suitability criteria for a high level waste repository. A report to Lawrence Livermore Laboratory, UCRL-13793.

Hackel, O., 1966, Summary of the geology of the Great Valley: Calif. Div. of Mines and Geol., Bull. 190, p. 217-238.

Harman, C. G., and Fraulini, F., 1940, Properties of kaolin as function of particle size: Am. Ceram. Soc. Jour. V. 23, p. 252-259.

Hower, J., Eslinger, E. V., Hower, M. E., and Perry, E. A., 1976, Mechanism of burial metamorphism of argillaceous sediments: 1 Mineralogical and chemical evidence: Geol. Soc. of Am. Bull. V 87, p. 725-737.

King, P. B., 1951, The Tectonics of Middle North America, East of the Cordilleran System, Princeton Univ. Press, New Jersey, 203 p.

Kirby, J. M., 1943, Upper Cretaceous stratigraphy of the west side of the Sacramento Valley, South of Willows, Glenn County, California, Am. Assoc. Petr. Geol., Bull. V. 27, p. 270-305.

Lee, W. T., 1927, Correlation of geologic formations between east central Colorado, central Wyoming, and southern Montana, U.S. Geol. Surv. Prof. Pap. 149, 80 p.

Levorsen, A. I., 1967, Geology of Petroleum, 2nd Ed., W. H. Freeman & Co. Publ., San Francisco, 724 p.

Magara, K., 1973, Compaction and fluid migration in Cretaceous shales of western Canada: Geol. Surv. of Canada, Pap. 72, 18, 64 p.

Maher, J. C., Carter, R. D., and Gantz, R. J., 1975, Petroleum geology of naval petroleum reserve No. 1, Elk Hills, Kern County, California: U.S. Geol. Surv. Prof. Pap. 912, 109 p.

Maxwell, D. T., and Hower, 1967, High grade diagenesis and low grade metamorphism of illite in the Precambrian Belt Series: Am. Mineralogist, V. 52, p. 843-857.

Maxwell, J. C., 1962, Origin of slaty and fracture cleavage in the Delaware Water Gap area, New Jersey and Pennsylvania: in Petrologic Studies (Buddington Volume), Geol. Soc. of Am., p. 281-311.

Mielenz, R. C., and King, M. E., 1955, Physical chemical properties and engineering performances of clays: Calif. Div. of Mines and Geol. Bull. 169: Clays and Clay Technology: p. 196-254.

Mintz, L. W., 1977, Historical Geology: The Science of a Dynamic Earth; Merrill Publ. Co., Columbus, Ohio, 588 p.

Murray, G. E., 1961, Geology of the Atlantic and Gulf Coastal Provinces of North America, Harper Bros., New York, N.Y., 692 pp.

Osborne, H. W., 1953, Symposium on fractured reservoirs. Discussion: Am. Assoc. Petr. Geol. Bull. V. 37, p. 318.

Page, B. M., 1966, Geology of the Coast Ranges of California: Calif. Div. of Mines & Geol. Bull. 190. p. 255-276.

Poole, F. G., and Sandberg, C. A., 1977, Silurian and Devonian paleogeography: in Paleozoic Paleogeography, Soc. Econ. Paleont. and Mines, Stewart, J. H., Stevens, C. H., and Fritsche, M. E., Ed. Pacific Coast Paleogeography Symposium 1, p. 39-85

Powers, M. C., 1967, Fluid release mechanisms in compacting marine mud rocks and their importance in oil exploration: Am. Assoc. Petr. Geol., Vol. 51, p. 1240-1253.

Rubey, W. W., and Hubbert, M. B., 1959, Role of fluid pressure in mechanics of overthrust faulting: Am. Assoc. Petr. Geol., Bull. V. 70, n. 2, p. 167-184.

Ruedemann, P., 1939, Geology of the south central lowlands and Ouachita Province: in Geology of North America, Ruedemann, P. and Belk, E., Edit., Verlag von Gebrüder Borntraegen, Berlin, p. 463-518.

Samuels, S. G., 1950, The effect of base exchange on the engineering properties of soils. Figure in Mielenz and King (1955) op. cit.

Schuchert, C., 1943, Stratigraphy of the Eastern and Central United States; John Wiley and Sons, Inc. Publ., New York, N.Y., 1013 p.

Seyfert, C. K. and Sirkin, L. A., 1973, Earth history and plate tectonics, Harper and Row Publ., New York, N.Y.

Smith, J. E., 1971, The dynamics of shale compaction and evolution of pore fluid pressures, Mathem. Geol., Vol. 3, no. 3, p. 239-263.

Smith, J. E., 1973, Shale compaction, Soc. of Econ. Petr. Eng., V. 255, p. 11-24.

Snow, T. D., 1968: Rock fracture spacings, openings. and porosities: Jour. of Soil Mech., Foundation Divisions Proceeding. Am. Soc. Civ. Eng., V. 94, p. 73-91.

Stewart, J. H., and Suczek, C. A., 1977, Cambrian and latest Precambrian paleogeography: Paleozoic Paleogeography; Pacific Coast Paleogeography Symposium , n. 7, Soc. Econ. Pal. and Mines, Stewart, J. H., Stevens, C. H., and Fritsche, H. E., Edit., p. 1-19.

Tourtelot, M. A., 1962, Preliminary Investigation of the geologic setting of the Pierre shales, Great Plains region; U. S. Geol. Surv., Prof. Pap. 390, 74 p.

Towe, K. M., 1962, Diagenesis of clay minerals as a possible source of cement in sedimentary rocks: Jour. of Sed. Petrology, V. 32, p. 26-28.

Weaver, C. E., 1959, The clay petrology of sediments: in Clay and Clay Minerals, V. 6, p. 154-187.

Weaver, C. E., and Pollard, E., 1975, The chemistry of clay minerals, Elsevier Scient. Publ. Co., New York, N.Y., 213 p.

Webster, D. S., Proctor, J. F., and Marine, I. W., 1970, Two-well tracer test in fractured crystalline rock. U.S. Geol. Surv., Wat. Supp. Pap. 1544-I.

Yeh, H. W., and Savin, S. M., 1977, Mechanism of burial metamorphism of argillaceous sediments: 3-0-Isotope evidence: Geol. Soc. of Am. Bull. 88, p. 1321-1330.

NOTICE

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, or any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for any third party's use, or the results of such use, of any information apparatus, product or process disclosed in this report, or represents that its use by such third party would not infringe privately owned rights.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or any U.S. Government agency to the exclusion of others that may be suitable.