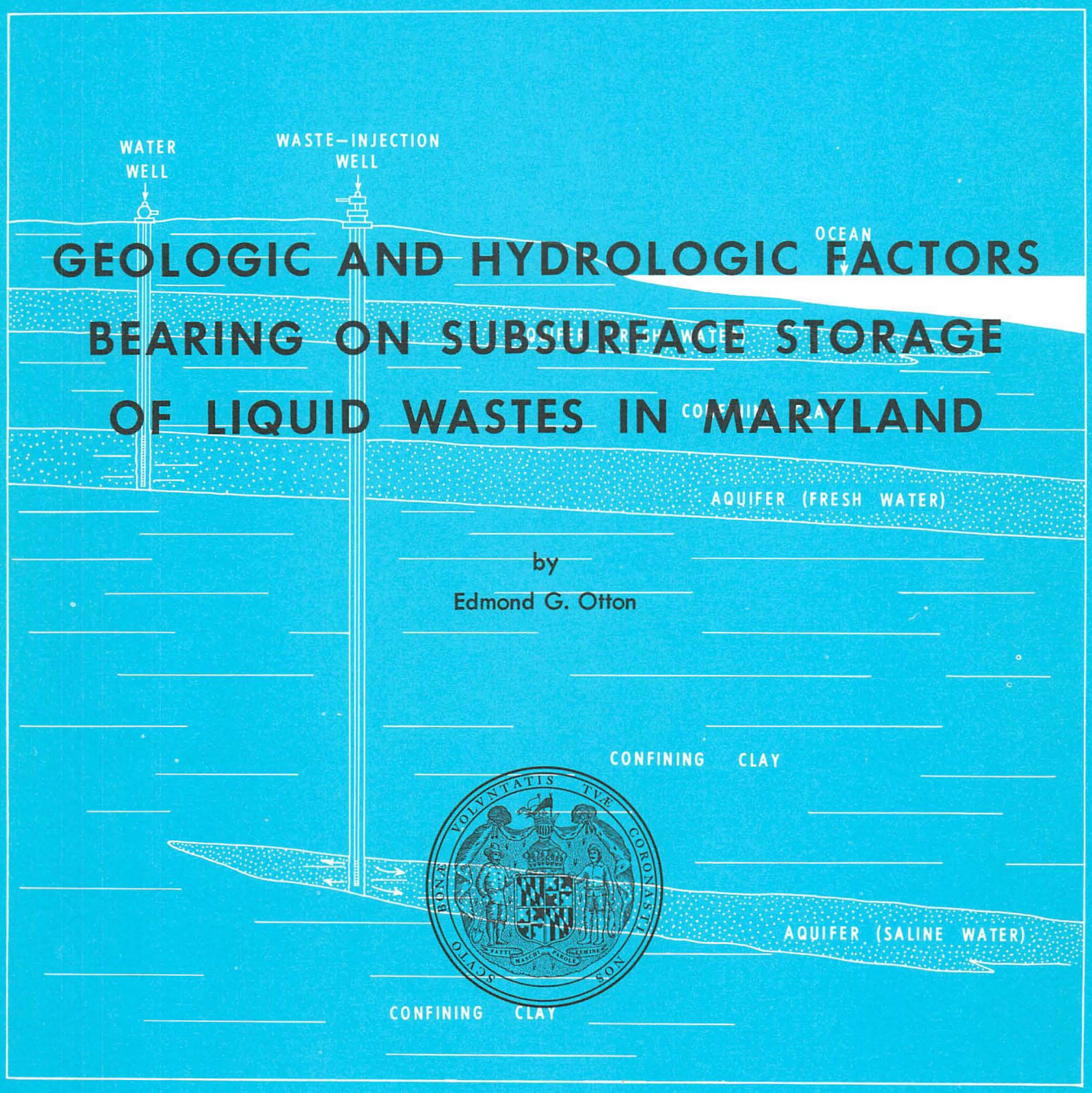
MARYLAND GEOLOGICAL SURVEY

Kenneth N. Weaver, Director

REPORT OF INVESTIGATIONS NO. 14



GEOLOGIC AND HYDROLOGIC FACTORS BEARING ON SUBSURFACE STORAGE OF LIQUID WASTES IN MARYLAND

by

Edmond G. Otton

Prepared in cooperation with the Geological Survey
United States Department of the Interior

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PREFACE

The storage of nonparticulate liquid wastes in deep saline aquifers is one method of waste "disposal." The "disposal" of effluent deep in the subsurface may be feasible in certain areas of Maryland without jeopardy to the environment outside of the storage zone. Having stated this, however, I must append to it two extremely important qualifications: One, at present, due to a lack of deep well data, no environmentally safe storage zone has been identified in sufficient detail to permit the injection of wastes into it. For each proposed storage zone specific and detailed data must be obtained concerning aquifer depth, thickness, and boundaries; rock type and permeability; pressure "heads" and gradients; and chemical composition of host fluids. Without these data any serious consideration of a deep well "disposal" project would be grossly premature.

Two, assuming that an acceptable storage zone can be delineated, it is then necessary to design a disposal well system that is capable of injecting effluent safely into the deep subsurface. Because injection wells must frequently be shut-in to rehabilitate the injection face, back-up systems are necessary. In addition continuous monitoring is required to detect any casing defects before significant leakage can occur. Clearly, only the most carefully engineered projects should be undertaken.

As Arthur Piper of the U.S. Geological Survey has noted, "There may be no perfectly safe way of disposal of wastes underground but we must review existing regulations and start collecting the kind of environmental data needed to assess the level of risk." The following report by Edmond G. Otton provides a start insofar as it has defined a hydrogeologic framework within which specific "disposal" zones can be evaluated in more detail.

KENNETH N. WEAVER, *Director*
Maryland Geological Survey

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GEOLOGIC AND HYDROLOGIC FACTORS BEARING ON SUBSURFACE STORAGE OF LIQUID WASTES IN MARYLAND

by

Edmond G. Otton

ABSTRACT

Factors that should be considered in deep-well waste injection include the hydraulic properties of the receiving rocks, the presence of impermeable confining layers above and below those rocks, the relation of waste injection to the presence of usable aquifers and of economic deposits of fuels and minerals, the chemical compatibility of the injected wastes and of the receiving rocks, engineering factors such as the construction and operation of the wells in such a way as to minimize leakage from casing failure and rock fractures along which the wastes could escape, and factors influencing the cost of deep-well injection in comparison to the costs of other methods of waste handling.

The State of Maryland is divided into three major regions and these, in turn, are divided into eight major subregions on the basis of physiography, geology, and hydrology and each is discussed in relation to deep-well injection of wastes.

In the Appalachian Region, there are several porous zones that might accept injected wastes, and there are thick sequences of low-permeability rocks that might function as confining layers. In some places there are fresh-water zones that must be considered and in the eastern part of the Western Maryland subregion, there is extensive faulting that might permit vertical leakage of injected wastes.

In the Piedmont Region the highly metamorphosed and fractured rocks of the Catoctin Mountain belt offer few opportunities for practicable injection of wastes because of the low permeability and generally ineffective confining layers. In the Frederick Valley and Triassic Lowlands, faults, sills, and dikes offer possible routes for vertical leakage of injected wastes. Fracturing, faulting, low permeabilities, and general absence of extensive confining layers would appear to preclude safe waste injection.

In the Coastal Plain Region factors related to waste injection decisions range widely. Most of the aquifers contain fresh water in the Inner Coastal Plain and the number decreases seaward. In the Middle Coastal Plain, there appear to be several saline aquifers below a depth of about 2,000 feet and in the Outer Coastal Plain there are many. Throughout the Coastal Plain Region there are extensive thick confining layers.

INTRODUCTION

This report was prepared by the U.S. Geological Survey (Water Resources Division) as part of its cooperative program with the Maryland Geological Survey. The report provides hydrogeologic information needed to evaluate applications to inject waste liquids into subsurface rocks. The report includes guidelines for decision-making, but does not purport to set State policy; nor does it imply approval or disapproval of the practice of subsurface waste storage.

Interest in the possibility of storing liquid wastes underground is increasing rapidly nationwide as a consequence of enactment and amendment of the Federal Water Pollution Control Act. Enforcement of stream-quality standards established by the States under that Act has resulted, or will result, in the necessity for making many decisions whether to (1) increase the degree of treatment of a particular waste effluent to enable stream discharge without exceeding local tolerances for particular constituents under the stream-quality standards, (2) store the waste, with such pre-treatment as necessary, in a subsurface water-bearing formation (aquifer), or (3) find some other means of disposal.

The preference, from the standpoint of the industry or government agency generating the waste liquid, often hinges on cost. For the State agency or agencies having jurisdiction over the disposal of waste liquids, the decision involves not only costs to the waste disposer, but also overall costs to the State, including those of potential damage to the environment resulting from emplacement of wastes in, or escape of wastes from, the receiving aquifer.

The subsurface hydrogeologic environment is characteristically very complex so that it is never possible to predict with complete confidence what the effects of a given waste-injection operation will be. In judging the acceptability of a given application to inject waste underground, therefore, the State must balance potential costs and risks in the light of the best available information on subsurface conditions, seeking (1) to minimize the risk of escape of wastes, and at the same time (2) to avoid the economic loss involved in the relocation of an industry should subsurface disposal prove to be unacceptable.

The emphasis in this report is placed on assessment of the risks involved in subsurface waste storage because of the inherent lack of complete assurance that a proposed injection operation will go exactly according to plan.

In addition, nothing in this report is intended to convey the impression that any particular place, area, or depth zone in Maryland is suitable for subsurface waste storage in the absence of detailed specific information obtained by test drilling and pumping and test-hole surveying done at the proposed injection site. Even in areas and depth zones described as being of generally low risk character, detailed local information still must be obtained and it may be necessary for the State to reject a proposal, or modify it substantially on the grounds that the detailed information shows the risk to be too great at that particular site, or that approval is possible only with substantial modification of the proposal with regard to such aspects as treatment of the waste before injection, injection rate or pressure.

Deep-well injection of wastes is primarily a method of *storage* rather than of *disposal.* The wastes do not disappear; instead, they occupy space formerly occupied by native formation waters, and continuing success in an injection operation depends on the availability of additional storage space over time. The objectionable properties of some wastes may degrade with passage of time—for example, radioactive decay of an isotope of an element whose daughter product is unobjectionable in the concentrations present after decay. Or, objectionable qualities may be reduced by dilution as the waste moves through the aquifer as a part of its contained water. In any event, the objective of subsurface waste storage is to confine the injected liquid in the storage aquifer, either indefinitely or at least long enough for its objectionable properties to degrade before it enters a water-supply aquifer or emerges in a body of surface water. Obviously, the volume of the aquifer devoted to waste storage is unavailable for other uses, such as pumping of the native saline water for desalination, use of that volume for cyclic storage of fresh water, or mining of the mineral skeleton of the aquifer should it include particles of an economic mineral. Thus economic cost of commitment of the aquifer for waste storage instead of some other use must be considered in reaching a decision on each waste storage proposal.

This report provides guidance in the collection and evaluation of scientific and engineering information needed to evaluate the degree of risk associated with subsurface waste disposal through deep wells. It points to several considerations on which it is necessary for the State to arrive at

decisions on policies and procedures, by additional legislation if necessary. These may be described briefly as follows:

(1) It must be decided whether the burden of proof that the proposed operation will not endanger the environment must be borne by the applicant or by the State. In other words, must the applicant convince the State that the operation is free of undue risk before the State will grant a permit, or must the State convince the applicant, or the courts, that the proposed operation is hazardous before it can deny a permit?

(2) It must be decided by the State whether to require that the applicant consider all other possible methods of waste handling and show not only that subsurface storage is the most economical method but that it is the only economically feasible method.

(3) The State must decide the criteria by which it can judge the overall acceptability of a waste-injection proposal as against some other use of the aquifer. Shall waste storage in potable-water aquifers be prohibited entirely; if not, under what conditions may it be considered? As to saline aquifers, on what basis shall it be decided which may be used for waste storage and which may not—salinity of the water, depth to the aquifer, likelihood of need for the aquifer as a source of water for desalination in the near future, etc.?

(4) The State must decide whether subsurface waste storage will be permitted in the vicinity of deposits of presently or potentially valuable minerals, such as coal, oil and gas, or metallic ores. If so, what restrictions would be necessary as to distance from or depth below the deposit, etc.? Would waste storage be permitted in a zone above the mineral deposit, and if so under what restrictions?

(5) In addition to deciding who must accept responsibility for furnishing the geologic (including geochemical), hydrologic, and engineering information necessary for an evaluation of the risk associated with deep-well waste injection, the State must decide how to specify what is needed in a particular situation—whether to set up a list of detailed requirements or to leave the list general and utilize the judgment of the responsible State agencies and employees as to the adequacy of the information furnished.

(6) Similarly, the State must decide the scope and detail of requirements to be imposed prior to, during, and after the life of the project with respect to such things as permissible types of waste, permissible rates of injection and pressures, monitor wells or other monitoring procedures to be required, etc.

(7) The ultimate fate of the injected waste, in a properly controlled operation, may range from emergence in a body of surface water within a few years (but after there has been sufficient time for degradation of objectionable properties to an innocuous level), to movement in a deep aquifer, so slow that the expected time of egress would be thousands or millions of years. The State must decide the extent to which a showing must be made in regard to the fate of the waste and the time involved, as one of the requirements for consideration of the proposal.

(8) The question of financial responsibility for the effects of unintended escape of wastes must be resolved. This and other financial and legal problems involved in subsurface waste storage are beyond the scope of this report, but they must be recognized and resolved.

It is emphasized specifically here that the U.S. Geological Survey has no jurisdiction over the practice of subsurface waste storage and does not intend to imply either approval or disapproval of the practice by any discussion in this report—its role is simply to provide some of the scientific and technical information needed by those who have control authority. Such information presented in the remainder of this report includes facts on the current status of subsurface waste disposal, hydrologic and other factors bearing on subsurface waste disposal and pertinent hydrogeologic conditions as they exist in Maryland.

ACKNOWLEDGMENTS

The writer acknowledges the assistance provided through technical discussions with his coworkers in the Geological Survey and the several persons who have prepared scientific and technical reports describing the geology and ground-water resources of Maryland during the past 25 years or more. These latter sources of information were heavily drawn upon as a basis for the conclusions presented.

Dr. Grover Emrich of the Pennsylvania Department of Health furnished considerable information about current deep-well waste-storage operations in his State. C. L. McGuinness of the U.S. Geological Survey edited and revised the report and his assistance is gratefully acknowledged.

Miss Catherine Manly drafted the illustrations and Mrs. Mary E. Walters and Mrs. J. Elizabeth Smith typed the report.

CURRENT STATUS OF SUBSURFACE WASTE STORAGE

As of the time of preparation of this report (1969), no waste-injection wells were in operation in Maryland, nor were any planned so far as is known to the writer. Waste-injection wells in the United States number in the tens of thousands. All but a small fraction are brine-injection wells in petroleum-producing areas, through which waste brines are returned to the petroleum-producing strata or are injected into other strata containing native salt water. Brine injection has a long history and a rather sophisticated technology. Although actual or potential problems have developed in a number of areas (for example, see Irwin and Morton, 1969), the practice of brine injection benefits from the rather general compatibility of the waste brines with the fluids present in the source beds or the other salt-water strata into which the brines are injected and the fact that the brine, in effect, is being used to fill a well resulting from oil production. Hence, considering the number of active injection wells, the problems tend to be less severe than those encountered, or expected, in situations where the waste liquid is totally different in its chemistry from the fluids in the receiving aquifer and where it must be superimposed on them.

With the history of brine injection in mind, and considering the fact that Maryland produces no oil and only a moderate amount of natural gas, this report is concerned mainly with wastes other than petroleum brines.

No exhaustive national survey of waste-injection wells has been made. Don L. Warner (1967), formerly of the Federal Water Pollution Control Administration and now at the University of Missouri at Rolla, and the Interstate Oil Compact Commission (1968) have made reconnaissance surveys. According to these, as of early 1968 at least 124 wells for injection wastes other than petroleum brines had been constructed in 18 States; of these, 104 were in operation as of January 1968. According to informal reports from colleagues in the Geological Survey, interest in the practice is growing rapidly and pressure to increase the number of active wells is likely.

A wide variety of wastes other than brines are being injected through the deep wells that have been canvassed. These include wastes from petroleum refineries and natural-gas purification plants; chemical, petrochemical, and pharmaceutical plants; metal-products plants; paper mills; a nylon plant; photographic-processing plants; an aerospace facility; and others. In addition, some radioactive wastes are being disposed of, or considered for disposal, at Atomic Energy Commission installations and at plants licensed by that agency.

Following is a partial list of the chemicals identified by Warner (1967, p. 8-45) as being injected at specific sites in the United States:

1) Photographic-processing wastes, including bleaches, hardeners, developers, and fixers.
2) Basic liquid wastes containing ammonia, nitrates, chlorides, chlorates, chlorinated hydrocarbons, and organic phosphorus compounds.
3) Acetic acid solutions.
4) Hydrochloric acid solutions.
5) Sodium hydroxide, sodium carbonate, alcohol, ketones, and hexamethylenediamine.
6) Sodium and ammonium sulfates.
7) Phosphorus trichloride, ethanol, methyldichlorophosphine, and ammonium chloride.
8) Steel-pickling liquor, consisting of 10 percent sulfuric acid and 15 percent ferrous sulfate.
9) Acrolein, derivatives of acrolein, and aluminum hydroxide.
10) Phenols and mercaptans.
11) Waste derived from manufacture of chloromycetin.
12) Methylcellulose and propylene oxide.
13) Laundry wastes containing detergents and soap.
14) Acid solutions having small concentrations of thorium-230 and radium-226.

The listing above is far from complete, but is given primarily to suggest the range of wastes currently being stored in underground reservoirs and the problems that might result from escape of the more toxic wastes from the storage aquifer.

The reported rates of injection of the various fluids range from a few gallons per minute to more than 800 gpm. The typical injection rate is between 100 and 400 gpm.

FACTORS BEARING ON SUBSURFACE WASTE STORAGE

PROPERTIES OF ROCKS

Rocks considered for liquid-waste storage must have sufficient porosity, permeability, thickness, and areal extent to function as storage reservoirs for intended volumes of waste at safe injection pressures. Many sedimentary-rock aquifers would meet the requirements imposed by typical waste loads, which tend to be in the range of a few thousand to a few hundred thousand gallons per day—volumes that are not large in comparison to those of fresh water ordinarily extracted from aquifers. The common sedimentary-rock aquifers in Maryland are composed of sand, sandstone, limestone, and dolomite. Locally, beds of shale, where weathered, fractured, and lying near the land surface, yield small supplies of water to domestic and stock wells. The thickness and areal extent of a suitable reservoir stratum could range widely, but ordinarily a stratum less than a few tens of feet thick and a few square miles in extent would serve for storage of only a moderate volume of waste.

A second geologic factor governing the usability of a particular stratum for liquid-waste storage is the presence of low-permeability confining layers above and below the reservoir stratum. Clay and shale (except shale brittle enough to maintain open fractures and, hence, capable of acting as an aquifer) may constitute suitable confining strata, though not all such beds are sufficiently impervious. Russell (1960, p. 117) has stated that the minimum thickness of a confining layer to entrap petroleum need be only 10 to 20 feet if the layer is of very low permeability. Confining layers similar in thickness and character to those that effectively trap petroleum could be expected to trap most waste fluids.

Faults and other fractures in a stratum affect its suitability for deep-well liquid-waste injection. A body of consolidated rock permeable enough to carry water is likely to be competent enough to maintain open fractures—which, indeed, may constitute the principal element creating permeability—even if clay beds above and below are incapable of supporting such fractures. Hence, fracturing on a small scale may increase the waste-storage capacity of a rock. On the other hand, major fractures, such as faults, tend to cross several formations and extend to considerable depth, and they may act as conduits along which wastes could escape from the storage aquifer. The ability of such extensive fractures to carry liquids depends in part on the type of rock forming the walls. Incompetent rocks such as clay and soft shale may tend to cave into the fractures and close them off. Insoluble rocks, even though competent, may be ground into a fine paste by lateral or vertical movement along a fault, and this "gouge" may seal the fault and inhibit the movement of liquid either along or across the fault. Soluble rocks, such as limestone, dolomite, and gypsum, may dissolve out gradually along an extensive fracture and convert it into an equally extensive conduit. Rock salt, though even more soluble than the other rocks mentioned, tends to slump by plastic flow so that fractures tend to remain closed.

Faults and other major fractures can be located by means of detailed geologic mapping and the study and interpretation of core-hole data, drillers' logs, and geophysical logs. Under certain conditions, their presence may be deduced from irregularities in contour maps of the water table or potentiometric (artesian-pressure) surface.

According to Warner (1967, p. 8-45), the ages of the geologic units used for deep-well waste injection in the United States range all the way from Precambrian to Pleistocene, and depths of disposal wells range from a few hundred to more than 12,000 feet. Warner reports also that about 90 percent of the wells are less than 6,000 feet deep, and about 65 percent are less than 4,000 feet deep.

Sedimentary rocks are the most common waste-storage reservoirs, but Precambrian crystalline rocks have been used at the Rocky Mountain Arsenal at Denver, Colo., where waste fluids were injected during the period 1962-66 into a fractured gneiss at a depth of 11,975-12,045 feet. The operation of the disposal well was suspended in February 1966 because of evidence suggesting that the disposal may have been responsible for an increase in the frequency of earthquakes in the Denver area after 1962 (Evans, 1966; Healy and others, 1968).

Although deep injection wells have been drilled in various geologic terranes, most of the injection wells in the United States are in the Gulf Coast region and the North-Central Interior region. The Gulf Coast region is underlain by as much as several tens of thousands of feet of sand, clay, and carbonate rocks (marl, limestone, and dolomite)

of Cretaceous, Tertiary, and Quaternary age. Much of the North-Central Interior region is underlain by several thousand feet of sandstone, shale, and carbonate rocks of Paleozoic age. These rocks are veneered throughout a large part of the region by glacial deposits consisting of gravel, sand, silt, and clay and ranging in thickness from a few feet to a few hundred feet and, locally, as much as a thousand feet.

Although a small State in area (about 12,000 square miles), Maryland contains at least three major geologic and physiographic terranes.[1] These are the Appalachian mountainous terrane in the west; dissected Piedmont crystalline rock terrane in the central part; and the moderately dissected to flat Coastal Plain terrane in the east. The strata beneath the Coastal Plain in Maryland are somewhat similar to those of the Gulf Coast. Figure 1 shows the three major regions of Maryland, shows the location of places mentioned in this report, and indicates, by contours, the depth to basement crystalline rocks. Figure 1 will be discussed in greater detail in a subsequent section of the report.

HYDROLOGIC FACTORS

It is well known that oil and gas, commonly associated with brines, may be trapped in a permeable rock unit at the crests of upfolds (anticlines) where a suitable confining layer overlies the oil- and gas-producing zone. This entrapment occurs because the oil and gas are lighter than the associated brine and float on top of it. Conversely, if it is desired to store fluids having a density greater than that of the resident reservoir fluids, a structural downfold, or syncline, might be a favorable site for the injection of such high-density liquid wastes. This concept is discussed in detail by Warner (1965, p. 4), who suggests that permeable sandstone strata in synclines might be especially favorable sites for the storage of radioactive wastes. However, as he points out, the hydrodynamics of the aquifer must be thoroughly evaluated to ascertain if, under prevailing conditions, the waste fluid can be entrapped even in a syncline. This is because the flow of fluids in permeable rocks depends on hydraulic gradient as well as on the density of the fluids and the shape of the rock bodies. Where a continuous hydraulic gradient exists, the fluids may flow right across anticlines and synclines, just as water under pressure is able to flow upward as well as downward in pipes. Furthermore, few rocks are completely impermeable, and water may flow into or out of aquifers through supposedly "confining" beds at rates which, though small per unit of area, may reach a large aggregate volume where a cross-sectional area of several or many square miles is involved (Meinzer and Wenzel, 1942, p. 450).

Hence, the major hydrodynamic consideration involved in deep-well injection of liquid wastes relates to the circulation of water within the earth. In this connection R. L. Nace (written communication, 1969) of the U.S. Geological Survey has recognized a succession of ground-water zones, generally in downward order, in which fluid circulation is respectively *rapid, delayed, lethargic,* and *stagnant.* The zones are described as follows:

The zone of rapid circulation extends from the land surface downward some tens, or a few hundreds, of feet; the unsaturated zone (zone of aeration) and the uppermost part of the saturated zone are included. Here, commonly, the native soil water and ground water are unconfined, fresh, and largely of meteoric origin; the environment is oxidizing; and the residence time of the water ranges from a few hours to a few years. Natural discharge from the zone of rapid circulation is the principal source sustaining the dry-season flow of streams.

The zone of delayed circulation also contains native ground water which is largely of meteoric origin, is commonly fresh, but is ordinarily confined and nonoxidizing, especially at greater depths. The water circulates continuously but is retarded sufficiently by friction or by distance between recharge inlets and discharge outlets that natural residence time within this zone tends to range from a few decades to several centuries. The depth to this zone may range from no more than a few hundred feet in some geologic and topographic situations to thousands of feet in other situations. The deeper fresh-water artesian aquifers of the Coastal Plain are within the zone of delayed circulation.

The zone of lethargic circulation commonly contains highly mineralized water or brine. Although much of the water may have been of meteoric origin, its residence time is on the order of hundreds or thousands of years; the environment lacks free oxygen. The very slow fluid movement is generally considered to be hydrodynamic but

[1] The stratigraphic nomenclature used in this report is that of the Maryland Geological Survey.

may be in part under the influence of osmotic or other energy fields other than hydraulic. This zone is usually found at depths of hundreds or thousands of feet. The deepest brackish-water aquifers of the Maryland Coastal Plain probably are in the zone of lethargic circulation.

In the stagnant zone the rocks are porous, but the interstitial liquid (usually brine) appears to be hydrodynamically trapped. A small amount of movement may take place by osmosis or some other process not clearly understood. In general, the stagnant subzones are at least several thousand feet below the surface. Possibly sandstones lying 10,000 feet or more beneath the surface in western Maryland are in the stagnant zone.

It might appear from the above discussion that the zones of rapid and delayed circulation could be ruled out for waste storage, leaving only the lethargic and stagnant zones, especially the latter. Actually, it is not possible to generalize in this way, even if it were possible to determine unambiguously in which of the four categories a particular body of rock belongs; not even this can be done, because adjacent categories are completely gradational into each other. A particular waste might be stored with relatively low risk in a part of the zone of delayed circulation not committed to other uses, provided that it could be ascertained that confinement of the waste in the injection stratum could be assured with a high degree of confidence, and that the residence time in that stratum would be ample for degradation or dilution of the objectionable properties of the water. On the other hand, the stagnant zone is not necessarily one of low risk just because it is remote from the land surface by reason of depth or of thickness and low permeability of confining beds. The permeability of any particular target aquifer in that zone is likely to be low, so that a large volume of waste could be injected only under high pressure. In this event there might be danger of creating fractures in the confining beds that would permit the waste to escape from the injection zone; seismic disturbances also might result.

These points bring out further the cautions stated in the Introduction, to the effect that generalizations about the relative risks involved in subsurface waste storage are useful only as tentative guides to the scope and intensity of data gathering that must be undertaken as a basis for decisions on specific proposals at specific sites. The risks involved in subsurface waste injection can be evaluated adequately only when geologic and hydrologic conditions at and surrounding the proposed injection site are known well enough to indicate the level of confidence with which it can be assumed that the particular volume and type of waste can be injected and stored as intended.

EFFECT ON MINERAL RESOURCES

Storage of waste in an aquifer commits the portion of the aquifer involved to that use and hence, precludes the use of that portion for other purposes. This restriction applies, of course, to the entire area of the aquifer the waste will occupy, as it adjusts to the natural pattern of flow, or to a different pattern induced by pumping from wells some distance away—in other words, the area of the aquifer occupied by the waste not only as it is injected but also as it travels from the injection point toward an area of natural discharge or a point or area of artificial discharge.

Although few States have enacted recent legislation designed specifically to govern the practice of subsurface waste storage, there seems to be a consensus that use of fresh-water aquifers for waste storage will be prohibited, or permitted only under unusual circumstances. Thus, all or most storage of waste will involve saline aquifers. But such aquifers are at least potentially usable as sources of water for desalination, or as storage media for fresh water injected so as to flush out the saline water from a particular volume of the aquifer. Where the native water is highly saline or a brine, it may contain valuable dissolved mineral constituents such as magnesium. It is even possible that the aquifer itself may consist in part of particles of an economic mineral, such as the phosphate sands described by Brown (1958).

Hence, an assessment by the State of the acceptability of a proposal to store waste underground must take into account other possible uses of the target aquifer in the area concerned, as well as the practicability of and the risks imposed by the proposed injection itself.

It appears that, generally, states where deep-well injection of liquid wastes is practiced have policies prohibiting waste storage that would conflict with the development of mineral resources, including coal, oil, gas, and other minerals. Although Maryland's policy in this regard is not settled, it is worth while to describe briefly the principal mineral occurrences in the State.

The only coal-bearing strata in Maryland occur in five structural troughs or basins in the two westernmost counties, Allegany and Garrett. The

coal-bearing strata, which are of the Pennsylvanian System of Paleozoic age, extend to maximum depths of 1,600 to 1,800 feet in the Georges Creek basin in western Allegany County (Amsden, 1954, p. 47). However, the lowest coal bed described in the literature as workable lies more than 200 feet above the base of the strata of Pennsylvanian age. Thus, even in the deepest part of the Georges Creek basin, coal mining is not likely to take place below depths of 1,400 to 1,600 feet. Provision of an adequate thickness of impervious strata between the deepest workable coal bed and any potential waste-storage horizon would require injection at depths of at least a few thousand feet. However, in recent years the method of mining has changed from underground to strip mining. It is probable that any deep-well injection of waste that might be considered in the coal-bearing areas would, if properly controlled, be unlikely to affect strip mining.

Four natural-gas fields have been discovered in western Maryland, and many exploratory wells have been drilled in Garrett, Allegany, and western Washington Counties in search of gas. The gas fields are at Mt. Lake Park, Accident, Negro Mountain, and Green Ridge (Edwards, 1969, p. 27). The Accident field is being converted to a gas-storage field, and the Green Ridge field is currently (1969) shut in. All gas production in the State comes from formations of the Oriskany Group of Devonian age. The deepest exploratory gas well (as of 1969) was drilled to a depth of 8,809 feet in the Accident field in Garrett County. Liquid waste storage in the vicinity of a natural gas field might adversely affect the utilization of this resource.

Other mineral resources in Maryland, such as clay, sand and gravel, limestone, marble, and mineral pigments, are all produced at shallow depths above or within the zone of potable ground water (zone of rapid or delayed circulation). On the assumption that any waste-injection project would be constructed and operated so as to prevent any escape of wastes into the potable-water zone, it may be expected that subsurface waste storage will not affect the extraction of these mineral products.

Water can be defined as a mineral resource, and water is the major resource of Maryland most likely to be affected by subsurface waste storage. Because of the wide range of geohydrologic conditions in the State and the complex variables involved in water occurrence and movement, most of the remainder of this report is devoted to discussion of the relation of subsurface waste storage to surface and ground water.

CHEMICAL FACTORS

The U.S. Public Health Service (1962) has fixed a preferred limit of 500 and a permissible limit of 1,000 mg/l (milligrams per liter) of dissolved solids for drinking water used on interstate carriers. Water containing less than 1,000 mg/l of dissolved solids is considered to be fresh, according to Krieger and others (1957, p. 5). These authors, in accordance with general usage in the U.S. Geological Survey, have classed water containing 1,000 mg/l or more of dissolved solids as follows:

Description	*Dissolved solids (mg/l)*
Slightly saline	1,000 to 3,000
Moderately saline	3,000 to 10,000
Very saline	10,000 to 35,000
Brine	35,000+

For purposes of deep-well injection, the Illinois Sanitary Water Board (Bergstrom, 1968, p. 2) has designated water containing less than 5,000 mg/l of dissolved solids as fresh, and no approval for deep-well waste injection is given where the disposal strata contain water having a mineral content less than that.

Water exceeding 2,000 mg/l in dissolved-solids content is not known to be used in Maryland for potable supply. It is possible, however, that, as desalination techniques are improved, water that is slightly or even moderately saline according to the classification given above may prove to be an economical source of potable supply for some communities.

If a deep-well waste-injection system is to operate successfully, it is important that the injected liquid and both the native water of the aquifer and the minerals of the aquifer itself be chemically compatible—that is, that injection of the new liquid will not cause chemical reactions that would interfere with injection. According to Selm and Hulse (1960, p. 140), the chief problems that are likely to arise as a result of chemical incompatibility are precipitation and polymerization. In either case, solids or gases may form, fill up the voids in the receiving aquifer, and thus reduce its porosity and permeability.

Tests have been made by some companies to determine the compatibility of waste liquids with resident fluids and with the receiving formation. Henkel (1955, p. 552) cites a company in Texas which conducted laboratory tests for chemical compatibility by mixing the resident and waste fluids for 8 hours at 60°C., the approximate temperature at the depth of injection. A second phase of the testing consisted of passing a representative sample of the waste material through cores taken from test holes drilled into the disposal aquifer.

Of course, the ultimate test for compatibility is made by measuring actual rates of injection, pressure buildup, and perhaps other phenomena such as temperature changes, after completion of a disposal well. But economic common sense argues that the possibilities should be evaluated as thoroughly as possible beforehand, in order to reduce the likelihood of having to abandon an expensive well.

Experience with artificial recharge of fresh water through wells has shown that even small concentrations of suspended sediment tend to clog the aquifer at and near the well bore. The same situation applies to waste injection, and the requirement for a liquid as clear as possible is even more stringent. This is because any injection well may have to be backpumped and flushed periodically to remove clogging materials. Repumped waste is, of course, more difficult and hazardous to handle than the generally innocuous water pumped from a fresh-water recharge well, so that it is naturally desirable to reduce the frequency of such operations by starting with as sediment-free a waste as possible.

It is not always possible to remove all sediment from a waste before injection. In such situations, the injection zone must be capable of accepting turbid liquid. In some places, cavernous limestones of high permeability have accepted waste liquids containing surprisingly large quantities of suspended material. As an example, Talbot (1968, p. 109) indicates that liquid sludge containing 3 percent of solids on a dry-weight basis has been injected into the Dundee Limestone at Midland, Mich. The material has been injected for more than 3 years at a rate of 60 gpm.

Donaldson (1964, p. 4) indicates that the successful disposal of certain types of liquid waste requires the addition of small amounts of bactericides to the disposal fluid to prevent the growth of microorganisms. If this is not done, the bacterial colonies, chiefly slime formers, may reduce the effective size of the injection pipe or may clog the formation face at the well bore.

ENGINEERING FACTORS

A prime consideration in the successful operation of a disposal system is the proper design and construction of the disposal well. Proper well design is based on thorough and complete geologic data obtained from holes drilled, logged, cored, and tested at the proposed injection site. Logs (various electrical and radioactive logs, caliper and sonic logs, sample logs based on examination by the driller and by geologists), tests on cores (porosity, permeability in different directions, mineral types, pore geometry), pumping and injection tests on different strata separated as necessary by packers and chemical analyses of water samples should be comprehensive enough to provide a high level of confidence that the waste will be accepted and contained as intended.

Protecting the overlying and underlying formations from contamination requires adequate casing, using materials immune to or protected from attack by the liquids or suspensions to be injected, sealing of the annular space around the casing with cement grout, and inclusion of leak detection systems. The construction of a relatively simple injection well, one of many different types that might be used in various situations, is shown in figure 2.

A common practice is to fill the annulus between the injection pipe and the well casing with oil or other corrosion-inhibiting fluid and then to install a pressure-monitoring gage in the inert fluid to detect any possible leakage from the injection string. The inert fluid is contained in the annulus by means of a packer located just above the top of the disposal zone. Corrosion resistant casing, as well as other fittings, must be of sufficient strength to withstand injection pressures, which may be as great as several thousand pounds per square inch at the injection level.

Because most rock formations physically suitable for waste injection are at depths of several hundreds or thousands of feet, initial hydraulic heads as measured at the injection level may be large, and fluid could be injected into these aquifers only by applying hydraulic pressure in excess of the formation pressure. The pressure required for injection at a given rate will increase with time, in accordance with the Theis equation, even if no clogging develops. Greater rates of increase in injection pressure would be required for aquifers of low permeability than for aquifers of high permeability. This is shown in figure 3 for two hypothetical aquifers whose average permeability is in the ratio of 1 to 5. The slopes of the lines

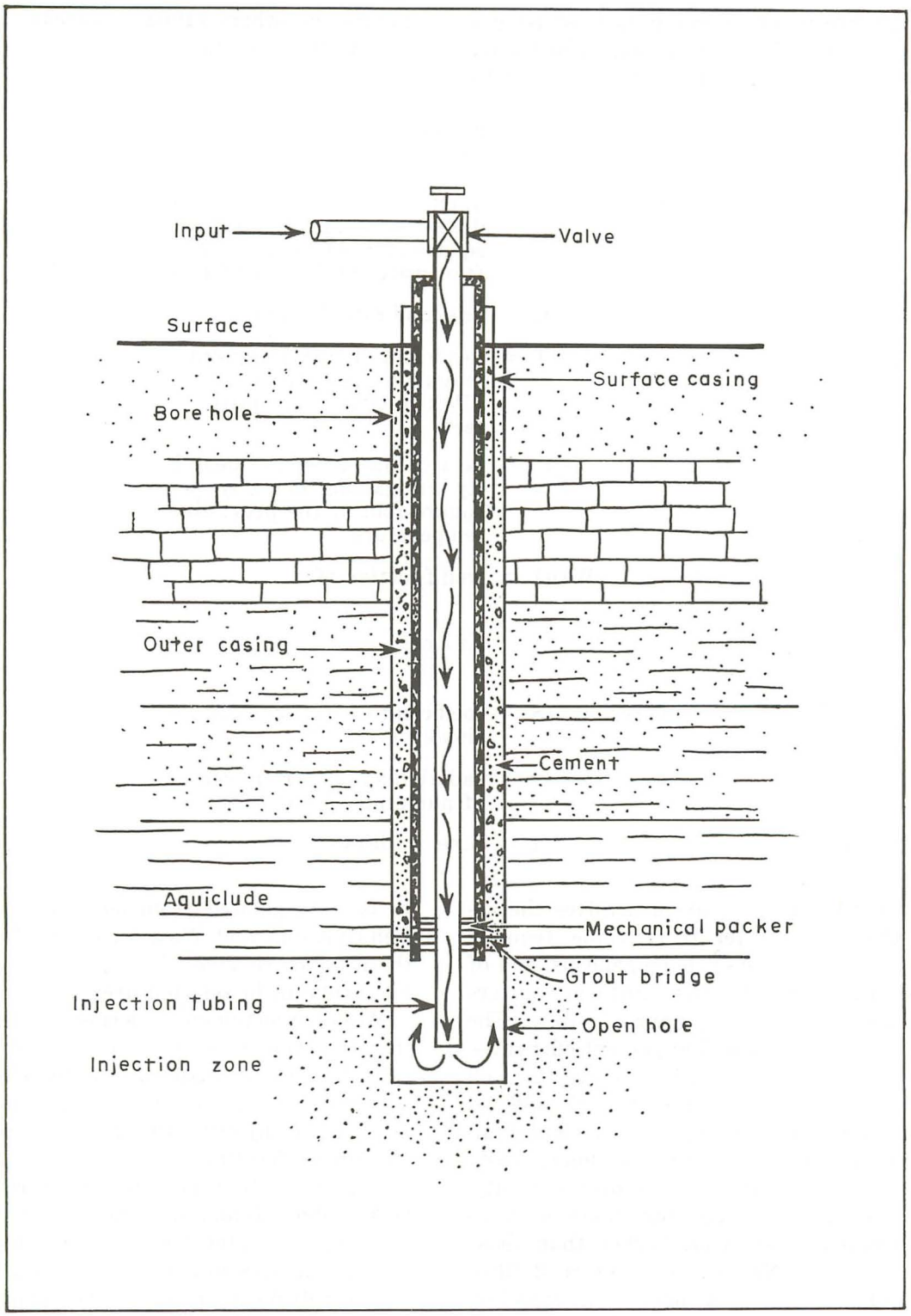

Figure 2. Sketch showing construction of a typical waste-injection well (Adapted from Walker and Stewart, 1968).

on the graph are based on computations using a modification of the Theis equation. The theory and limitations of the equation are discussed by Ferris and others (1962, p. 92-93). The formula used in the computations is:

$$ip = \frac{49.9\,Q}{T}\,W(u)$$

where:

ip = input pressure, or reverse drawdown, in pounds per square inch (1 lb/in^2 = 2.31 ft of water at density of 1.0)

Q = injection rate, in gpm

T = coefficient of transmissibility, in gallons per day per foot (P_f x thickness of aquifer in feet)

P_f = field coefficient of permeability, in gallons per day per square foot at the prevailing temperature

W(u) = well function of u

and:

$$u = \frac{1.87\,r^2S}{Tt}$$

where:

S = coefficient of storage (dimensionless)

r = radial distance from center of pumping, in feet

t = time, in days

The use of the Theis equation involves the assumption that the aquifer is isotropic (equally permeable in all directions), homogeneous, and of infinite extent. Even extensive, uniform aquifers meet these requirements only approximately. The input well is assumed to be 100-percent efficient—that is, that there is no head loss across the well face. Because no wells are this efficient, and because input wells are usually less efficient than discharging wells, especially for injection of waste fluids that are turbid, dense, or of high viscosity, the input pressures required for injection wells probably would be somewhat higher than those shown in figure 3. Nevertheless, figure 3 illustrates roughly the expected increase in injection pressures in disposal systems and shows that the rate of increase for a constant injection rate would be significantly greater for aquifers of low permeability than for aquifers of high permeability.

Because relatively few wells have been drilled for oil or gas in Maryland, few permeability measurements are available for the deep strata containing saline waters. Data of this nature had to be extrapolated from adjacent States, chiefly Pennsylvania and West Virginia. In this report these data are given in tables showing the geologic column in selected areas.

Where injection-zone permeabilities are so low that injection rates per well would be impractically low if the waste had to be accepted by the natural pore space of the rock, consideration may be given to injecting the liquid at pressures high enough to fracture ("hydrofrac") the rock and thus increase both porosity and permeability. At Oak Ridge, Tenn., a cement slurry containing radioactive wastes has been injected into horizontal fractures so created in a thick bed of shale. In the petroleum industry, the permeability of a producing zone may be increased by hydrofracking the rock with oil containing sand; the grains of sand bridge the newly created fractures and keep them open after the pressure is reduced.

The problem is to control the direction and extent of fractures—in essence, to create fractures that conform to the stratification and so are horizontal, or nearly so; and to avoid creating vertical fractures that might extend beyond the injection

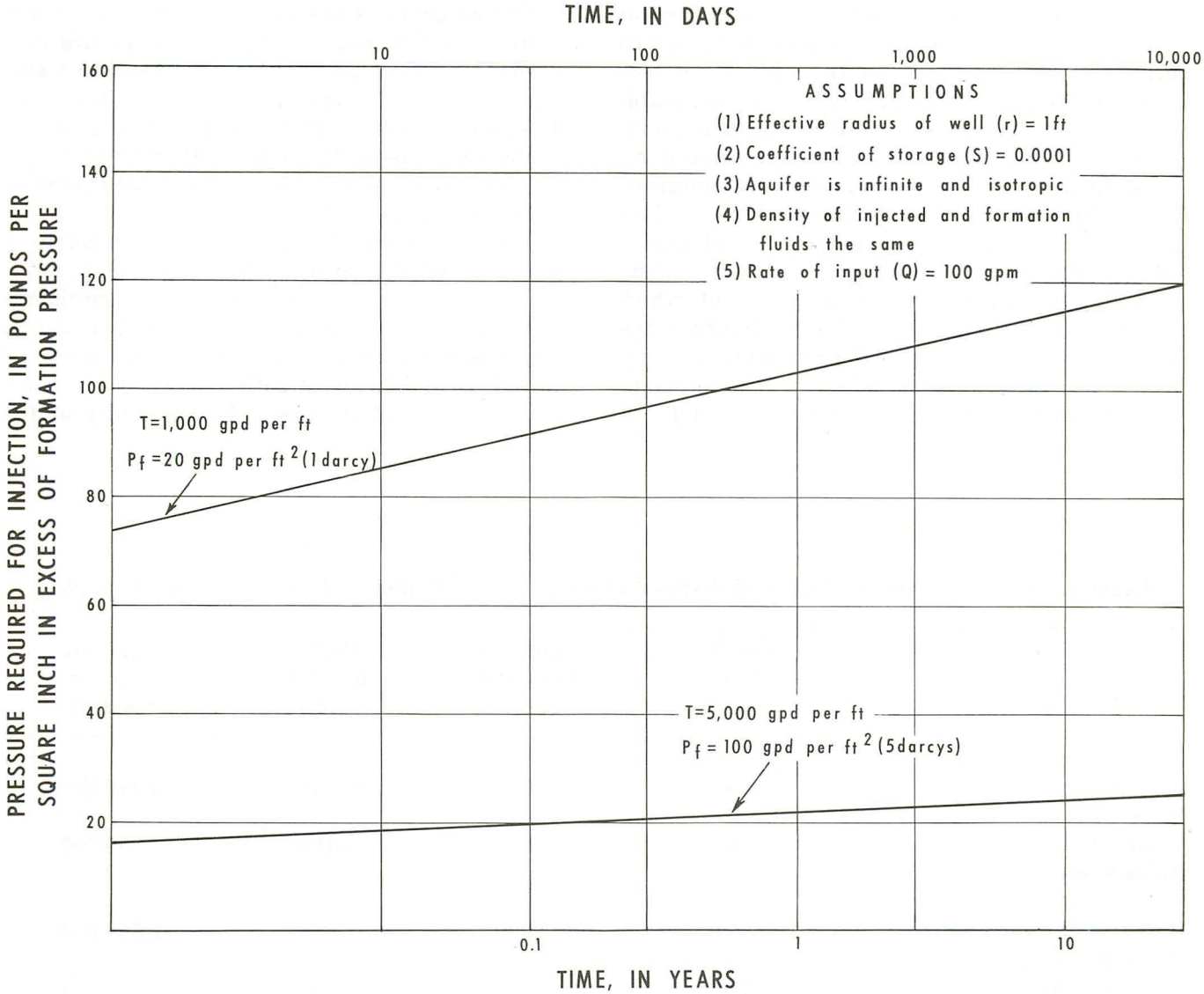

Figure 3. Graph showing theoretical increase with time of injection pressure required for wells in two aquifers having different hydraulic properties.

zone through the confining beds and thus permit escape of the waste. Considerable experience has been gained in the petroleum industry, but additional study and experimentation are needed to assure control of the fracturing to prevent escape of waste. Hence, in the States where subsurface waste injection is practiced, it is ordinarily required that, to prevent undesired effects from hydrofracking, injection pressures be kept below some specified fraction of "lithostatic pressure," the pressure exerted by the weight of all the rocks and their contained fluid lying above the injection zone. Representative values of permitted pressure in several States where brine injection is practiced are given by Irwin and Morton (1969).

ECONOMIC FACTORS

Deep-well injection of waste is one of two or more alternative methods of waste disposal that may be considered in competition with each other. According to circumstances, others might include stream disposal, with such dilution or pretreatment as necessary to maintain stream-quality standards; permanent storage of the waste in surface facilities; export of the waste; changes in plant processes to reduce the volume or toxicity of the waste; and even transfer of the installation to another site where the cost of waste disposal would be less.

As suggested previously, the company or agency having the waste to dispose of is concerned primarily with the costs of the various alternatives, under the particular constraints applicable to each; these constraints often include public opinion and relations as well as more directly related factors. The licensing agency is concerned primarily with the public welfare, which involves protection of the environment from undesirable effects of waste disposal ranging from mildly annoying to dangerously hazardous; but which involves also the public benefits resulting from the presence of such things as a productive industry which may have to be closed down if an economical means of waste disposal cannot be found.

The economic issues are especially acute where water supplies and waterborne wastes are concerned. Though units costs of obtaining water and disposing of wastes may be small, the quantities involved are commonly such that a large percentage increase in the cost of either water supply or waste disposal may turn a profitable operation into a losing one.

The economics of deep-well waste injection is discussed by Walker and Stewart (1968, p. 957). They state that, in addition to other considerations, a decision to utilize deep-well injection might be based on the following cost factors: (1) initial feasibility investigations; (2) location of a suitable disposal stratum; (3) suitability of the

Table 1. Costs of various deep-well disposal systems (from Walker and Stewart, Table 4, p. 958)

Type of waste	Injection rate (gpm)	Injection pressure (psi)	Depth of well (feet)	Total cost of system (dollars)
Brine and chlorinated hydrocarbons	200	500	12,045	1,419,000
Basic material, pH 10	70	1,000	6,160	250,000
Acids and other liquids from metal working and hydrostatic testing	250	400-1,200	5,880	1,558,000
Manufacturing waste, pH 1 to 9—variable	400	vacuum	4,150	700,000
Lachrymator waste from acrolein and glycerin units	700	150-170	1,960	135,000
Sulfuric acid waste	400	vacuum	1,830	562,000
Detergents, solvents, and salts	254	280	1,807	300,000
Aqueous solutions—phenols, mercaptans and sulfides	215	30-90	1,795	30,000
Spent pulping liquors	338	1,330	1,710	1,000,000+
Organic waste	60	500	1,472	400,000
Manufacturing waste, various organics and nonorganics	1,100	235	1,400	1/10 of that required for conventional bio-oxidation systems
Coke oven phenols and quench waters	50	300	563	25,000
Sulfuric acid pickling liquors	100	4,150	not given	1,300,000

waste for injection; (4) well construction and completion; (5) support equipment and operation; (6) maintenance and repair; and (7) standby and safety equipment.

Consideration of deep-well waste injection generally involves the drilling of one or more exploratory holes to determine the geologic conditions at the site, especially the existence, continuity, and horizontal extent of a disposal stratum and suitable confining layers above and below. According to circumstances, overall costs may possibly be reduced by converting exploratory holes into injection and, if required, monitor wells. Other factors to be evaluated include the cost of preparing the waste in a form suitable for injection, the cost of support equipment, and the cost of operation and maintenance. Walker and Stewart (p. 958) list a number of systems whose costs ranged from $25,000 to $1,558,000. Injection rates are reported to range from 50 to 1,100 gpm and injection pressures from 30 to 4,150 psi (pounds per square inch). Their data are given in table 1.

Cost breakdowns for components of individual systems in published reports are meager. Walker and Stewart (p. 959) list the approximate costs of a disposal well at New Orleans, La., as follows:

Item	*Cost*
1) Central chemical collection system	$284,711
2) Well drilled and cased to 6,665 feet	238,617
3) Support equipment (piping, valves, and pumps)	100,505
4) Reworking well (done four times in 2 years)	869,105
5) Normal maintenance cost (< 2 years)	65,000
Total cost	$1,557,938
Total waste injected as of January 1, 1967, 300 million gallons	
Cost per 1,000 gallons of waste injected	$5.19

Wright (1969, p. 27) presents, in summary form, the comparative costs of elements of deep-well injection systems for three major regions in the United States. These data are given in table 2.

It is apparent that a wide range of costs may be expected for deep-well injection systems, but whether these costs are rated high or low is determined by comparison with the costs of alternative methods of liquid-waste disposal.

Table 2. Comparative installation and operating costs of deep-well waste-injection systems in three major regions in the United States

Item	Great Lakes	Midcontinent	Gulf Coast
Number of wells	12	6	17
Average depth (feet)	3,290	3,580	3,200
Average cost per well	$294,400	$175,300	$362,400
Average cost per foot	$90	$50	$110
Average injection rate, in million gallons per well per year	62.3	68.2	69.0
Average annual operating cost (dollars per 1,000 gallons)	$0.42	$0.16	$0.17

CRITERIA FOR EVALUATING RISKS ASSOCIATED WITH DEEP-WELL WASTE STORAGE

Geologic, hydrologic, chemical, and engineering criteria are used to evaluate the benefits resulting from, and the risks or hazards associated with, injection of wastes through wells into the rocks beneath any given area. The pertinent requirements are as follows:

(1) An aquifer must be present which is, or which contains zones that are, sufficiently porous and permeable to accept and store liquid wastes.

(2) Confining strata having sufficient thickness and areal continuity to confine injected wastes within the waste-storage aquifer must exist above and below that aquifer.

(3) Faults, joints, and other fractures, if present, must not constitute conduits through the confining beds along which wastes could escape from the storage aquifer. In addition to the condition of existing fractures under preinjection conditions, consideration must be given to the possible effects of pressure injection of wastes in enlarging existing fractures or creating new ones.

(4) In addition to natural fractures such as faults and joints, consideration must be given to artificial openings such as abandoned wells, through which wastes might escape into other aquifers or escape to the land surface. Any such openings must be located and completely plugged by methods that will prevent them from acting as conduits for the indefinite future.

(5) As to any given area or region, it is assumed that, generally, storage of waste will be considered only for aquifers lying below, and separated by an adequate thickness of confining beds from, the deepest lying stratum from which water or other minerals are produced at present, or the possible future production of water or minerals from which is considered by the State to constitute a use preferential to waste storage. Should consideration of waste storage in a zone lying above a currently or potentially productive economic zone be permitted, it is assumed that (1) any abandoned wells or shafts extending into or through the waste-storage zone would be located and plugged as in (4) above, (2) operating wells or shafts extending through the waste-storage zone into the economic zone below would be reconstructed as necessary to prevent, for the indefinite future, any escape of wastes into them or along them into zones above or below, and (3) the waste-injection wells themselves of course would be constructed to assure that wastes could not escape from the storage aquifer.

(6) Although it is for the State to decide under what conditions, if any, storage of wastes in potable-water aquifers is to be considered, the actual and potential value of all aquifers, potable and saline, and of other subsurface zones actually or potentially useful for their contained fluids or minerals, must be considered in relation to the economic and other benefits of storing waste in such zones and to the risks of potential damage to such zones resulting from storage of wastes in other zones in the same area or region.

GEOLOGIC AND HYDROLOGIC CONDITIONS PERTAINING TO DEEP-WELL WASTE STORAGE IN REGIONS AND SUBREGIONS OF MARYLAND

In accordance with the previous discussion the following material describes the geologic and hydrologic conditions in the regions and subregions of Maryland with regard to the hazards of and opportunities for deep-well waste storage. The information presented should serve as a guide to indicate the type and scope of geohydrologic information needed by the State, in combination with other available information, for decisions regarding the acceptability of specific proposals for deep-well waste storage.

As stated previously (p. 7) Maryland is subdivided into three major regions (or provinces), chiefly on the basis of the distribution and physiographic expression of the important rock types. However, within the three regions of the State geologic and hydrologic conditions are significantly different. Based on these differences eight subregions have been described within the three major regions. The different geologic and hydrologic conditions occurring in the subregions result in the expectation of different degrees of risk or hazard regarding the practice of underground waste disposal. For example, the geology and hydrology of the Coastal Plain region differ from place to place between the northwest border at the Fall Zone to the southeast border along the Atlantic Ocean. Changes in the geology and hydrology southeastward from the Fall Zone are due to the thickening of the strata from 0 to 10,000 feet and

to the great increase in mineralization of the water in many of the aquifers near the coast. Figure 4 shows the location of the subregions of Maryland and summarizes the pertinent geologic and hydrologic information, as it relates to deep-well storage.

The Appalachian, or westernmost, region extends eastward from the West Virginia line to the Piedmont border along the west edge of South Mountain. This region is underlain by an estimated 20,000 to 30,000 feet of folded and faulted consolidated sedimentary rocks, chiefly of Paleozoic age. These rocks in turn are underlain by hard, dense rocks of the Precambrian basement complex, which have not been penetrated in Maryland by drilling but whose presence is inferred by extrapolation from adjacent States. The Appalachian region is divided into two subregions, western Maryland to the west and the Hagerstown Valley to the east.

Western Maryland is underlain chiefly by sandstone and shale forming a series of parallel mountain ridges and valleys which grade into an upland plateau at the extreme west end of the State. The Hagerstown Valley is underlain by faulted and folded limestone and shale. The hydrologic properties of the rocks in the Hagerstown Valley subregion differ from those in the western Maryland subregion. In general, the limestones of the Hagerstown Valley are more productive aquifers than are the rocks in western Maryland.

The Piedmont region occupies the central core of the State and extends from South Mountain on the west to the "Fall Zone" on the east (see fig. 1). The entire Piedmont region covers an area of about 3,000 square miles, or about one-fourth the area of the State. As defined in this report the Piedmont includes the Blue Ridge subregion (Catoctin Mountain belt of this report),[1] the Frederick Valley and Triassic lowlands subregion, and the Central and eastern Piedmont subregion.

The Catoctin Mountain belt is underlain by very old metamorphic and igneous rocks, consisting chiefly of metabasalt, phyllite, granodiorite, and granite gneiss. These rocks are weathered to depths ranging from 0 to 50 feet or more, but the weathered mantle is thin or lacking on the mountain slopes. The physical and hydraulic properties of the rocks in the Catoctin Mountain belt are, however, similar to those of the central Piedmont subregion to the east.

The Frederick Valley and Triassic lowlands subregions occupy a broad valley lying east of the Catoctin Mountains and west of the central and eastern Piedmont subregion (fig. 4). The area is drained chiefly by the Monocacy River and is underlain by several thousand feet of shale, sandstone, and limestone. The geology and hydrology of these rocks are somewhat different from those of the older, more highly metamorphosed crystalline rocks in the remainder of the Piedmont region.

The Central and Eastern Piedmont Subregion lies east of the Frederick Valley and northwest of the Coastal Plain (fig. 4). The oldest rocks in Maryland lie in this subregion (Baltimore Gneiss of Precambrian age). The subregions are characterized by crystalline rocks extending to great depths. The geohydrology, as related to deep-well liquid waste storage for the Piedmont subregions, is described in subsequent sections of this report.

The Coastal Plain region of Maryland lies to the southeast of the Fall Zone, extending to the Atlantic Ocean (figs. 1 and 4). The region includes about one-half the area of Maryland (Vokes, 1957, p. 45). From the Fall Zone southeastward younger Coastal Plain sediments are underlain by a "floor" of much older crystalline rocks. Based on the increased thickness of the Coastal Plain strata to the southeast from the Fall Zone and on the increased mineralization of the ground water in the aquifers in the same direction, the Coastal Plain region is divided into three subregions, an Inner Coastal Plain, a Middle Coastal Plain, and an Outer Coastal Plain. The geohydrologic factors in these subregions that are pertinent to subsurface liquid waste storage are described in subsequent sections of this report.

APPALACHIAN REGION

Western Maryland

For the purpose of this report the subregion designated Western Maryland (fig. 4) includes all the State west of the Hagerstown Valley. The area is generally mountainous and includes several mountaintops having altitudes of 3,000 feet or more. The rocks are sedimentary and include chiefly sandstone, siltstone, shale, thin beds of limestone, and coal. The major drainage system is the Potomac River and its tributaries. The ex-

[1] This classification is slightly different from that of Vokes (1957, p. 37). who places the Blue Ridge subprovince in the Appalachian instead of the Piedmont province. It is used in this report because the hydrologic properties of the crystalline rocks of the Blue Ridge are more closely related to those of the Piedmont rocks to the east than to those of the Paleozoic rocks to the west.

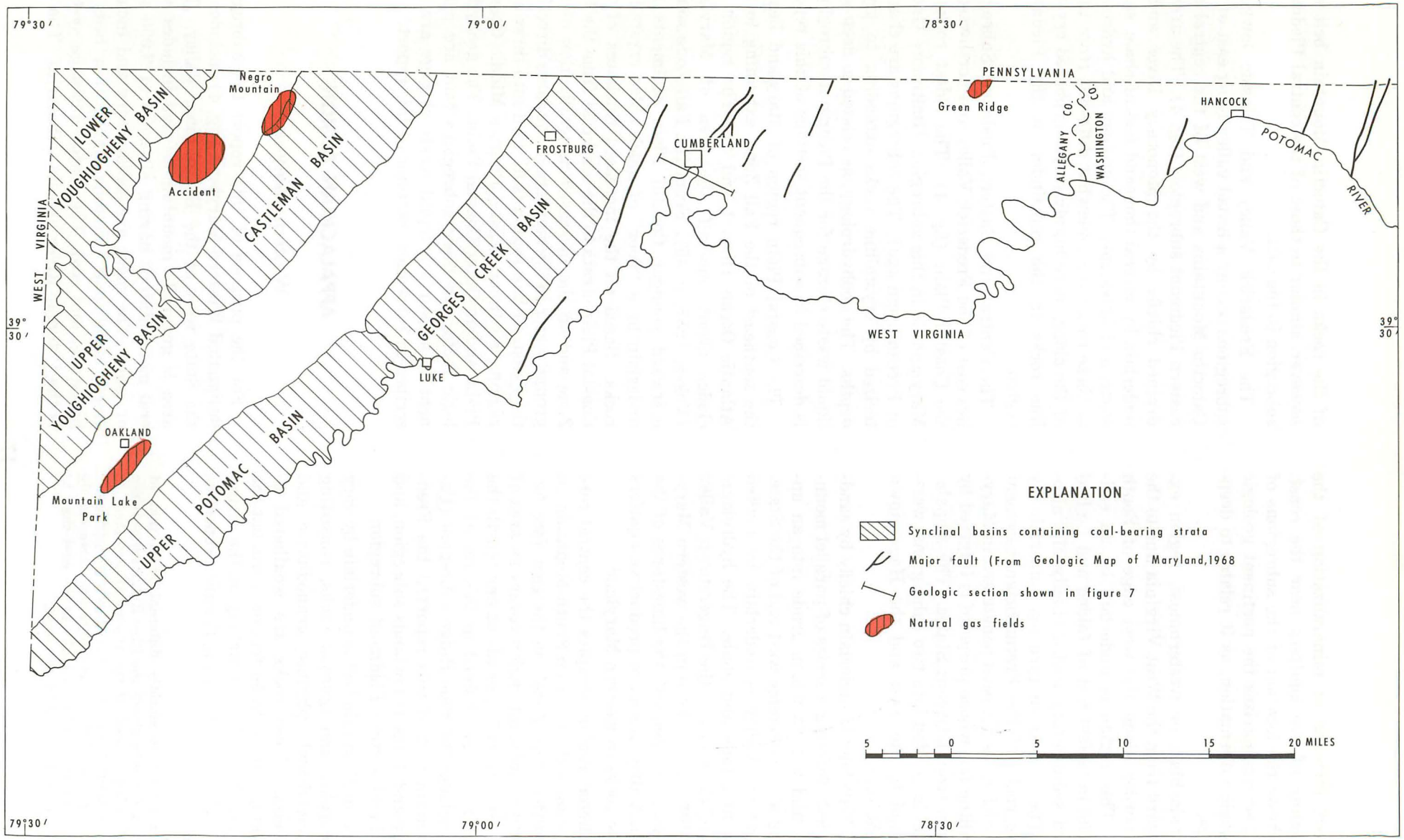

Figure 5. Map of western Maryland showing major geologic basins and faults.

posed rock strata range in age from Ordovician to Pennsylvanian and have been folded into a series of northeastward-trending anticlines and synclines. In general, the older strata are in the eastern part of the area and the younger strata in the western part. However, because of folding and faulting, some of the beds are exposed several times along an east-west profile across this part of Maryland.

The following geologic and hydrologic conditions in western Maryland must be considered when planning deep-well waste injection:

(1) Several porous and permeable limestone and sandstone strata are present. Some of them, however, yield fresh or saline water or, in Garrett and Allegany Counties only, natural gas. Economic coal beds are present.

(2) Several thousand feet of shale, mudstone, and claystone strata occur throughout the geologic section, and would probably function as suitable confining layers.

(3) The strata have been downwarped into several synclines or basins. According to the hydrodynamic situation under natural conditions, or that developing after injection began, such a basin might serve for long-term retention of wastes but this is not certain from general information available. A detailed drilling and testing program would be necessary for a decision.

(4) Faulting of the rocks is common in the eastern part of the area but appears to decrease in the western part. In some parts of the area the faulting is on a sufficiently small scale that it may not constitute a substantial hazard to deep-well waste injection, and, of course, even a major fault will not necessarily form a conduit for fluid flow. The Accident gas field is reported to be faulted but is tight enough to contain natural gas; on the other hand, a structure that will hold gas will not necessarily hold a liquid.

(5) The rocks decrease in permeability below depths of a few hundred feet, and the zones of rapid or delayed water circulation probably do not extend below depths of 1,000 to 1,500 feet. In many places potable ground water occurs only above a depth of 500 feet.

The sections of the report that follow describe conditions pertinent to deep-well injection in some of the synclinal basins in western Maryland.

Synclinal Coal-bearing Basins: There are five synclinal basins containing coal-bearing strata in Garrett and Allegany Counties. The locations and extent of the basins are shown in figure 5, which shows also the major mapped faults from

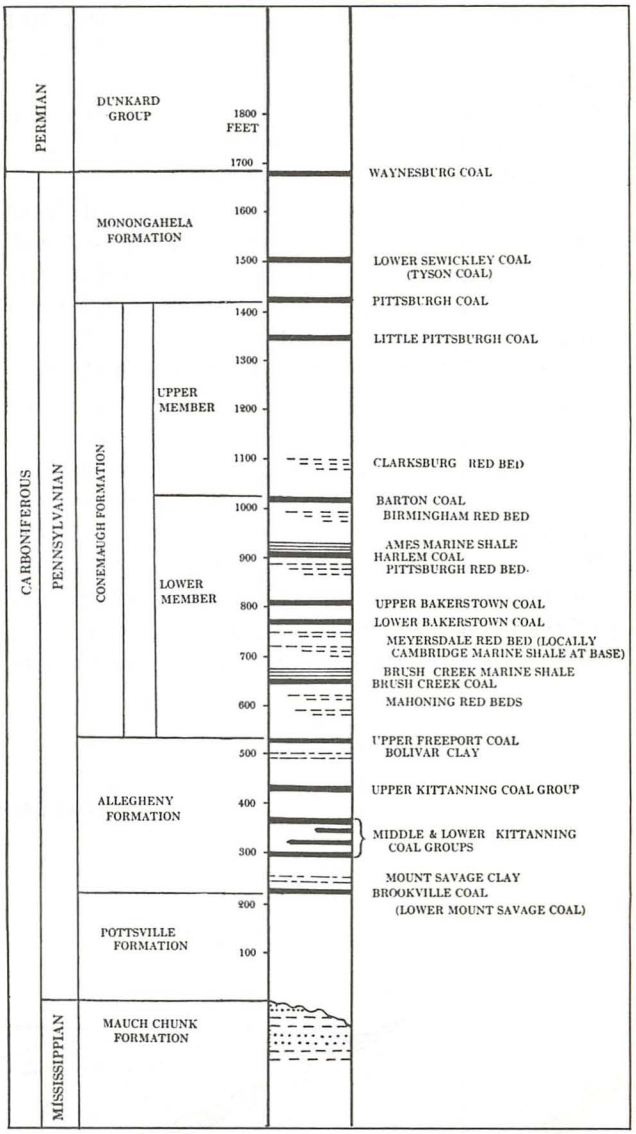

Figure 6. Generalized geologic section showing coal-bearing strata in the synclinal basins in western Maryland (From Amsden, 1954, p. 48).

the vicinity of Hancock to the West Virginia boundary.

The coal-bearing strata attain a maximum thickness of 1,600 to 1,800 feet in the Georges Creek and Upper Potomac basins (fig. 6). Although the coal measures include several permeable and porous sandstones as much as 100 feet thick, the presence of the economically valuable coals must be considered in any proposal to use the sandstones in the sequence for waste storage.

An additional factor to be considered in relation to the possible use of these sandstone beds for waste storage is the fact that the zone of rapid ground-water circulation may extend to depths of

more than 500 feet in some areas. Slaughter (1962, p. 115) reports that a fresh-water flow was obtained from a deep well near Frostburg at a depth of 490-512 feet. The water from this well had a dissolved-solids content of only 118 mg/l (milligrams per liter).

Slaughter (p. 138) also reports a flow of fresh water from a depth of 800 feet in a deep test well at Luke in the center of the Georges Creek basin. This water was obtained from the Mauch Chunk Formation of Mississippian age. The Luke test well (number All-Da 7) was drilled in 1948 to a total depth of 2,379 feet in a search for brine by the West Virginia Pulp and Paper Co. It is reported that water obtained from the Pocono Formation (Mississippian age) in the depth range of 1,521 to 2,379 feet had a dissolved-solids content of 16,000 mg/l. This water is very saline according to the classification of Krieger and others. The top of the Pocono Formation is reported to be about 1,300 feet deep at the site of the Luke brine test.

Although little is known of the details of the strata below depths of a few thousand feet in the center of the Georges Creek basin, extrapolation of the stratigraphic column from areas to the east and to the west indicates that at least three and possibly four formations might be considered for deep-well waste injection. These are: (1) the Pocono Formation, occurring in the center of the basin at an estimated depth of 1,300 to 1,500 feet; (2) the Oriskany Group, estimated to lie at a depth of 7,000 to 8,000 feet; (3) the Helderberg Formation, at a depth of 7,500 to 8,500 feet; and (4) the Tuscarora Formation, at an estimated depth of 9,500 to 10,500 feet. Use of the Pocono Formation for waste storage would require special precautions against vertical leakage because of its comparatively shallow depth. Similar precautions would need to be taken in the other four basins also, but the depths to formations that might be targets for waste storage may be different from those given above. At present

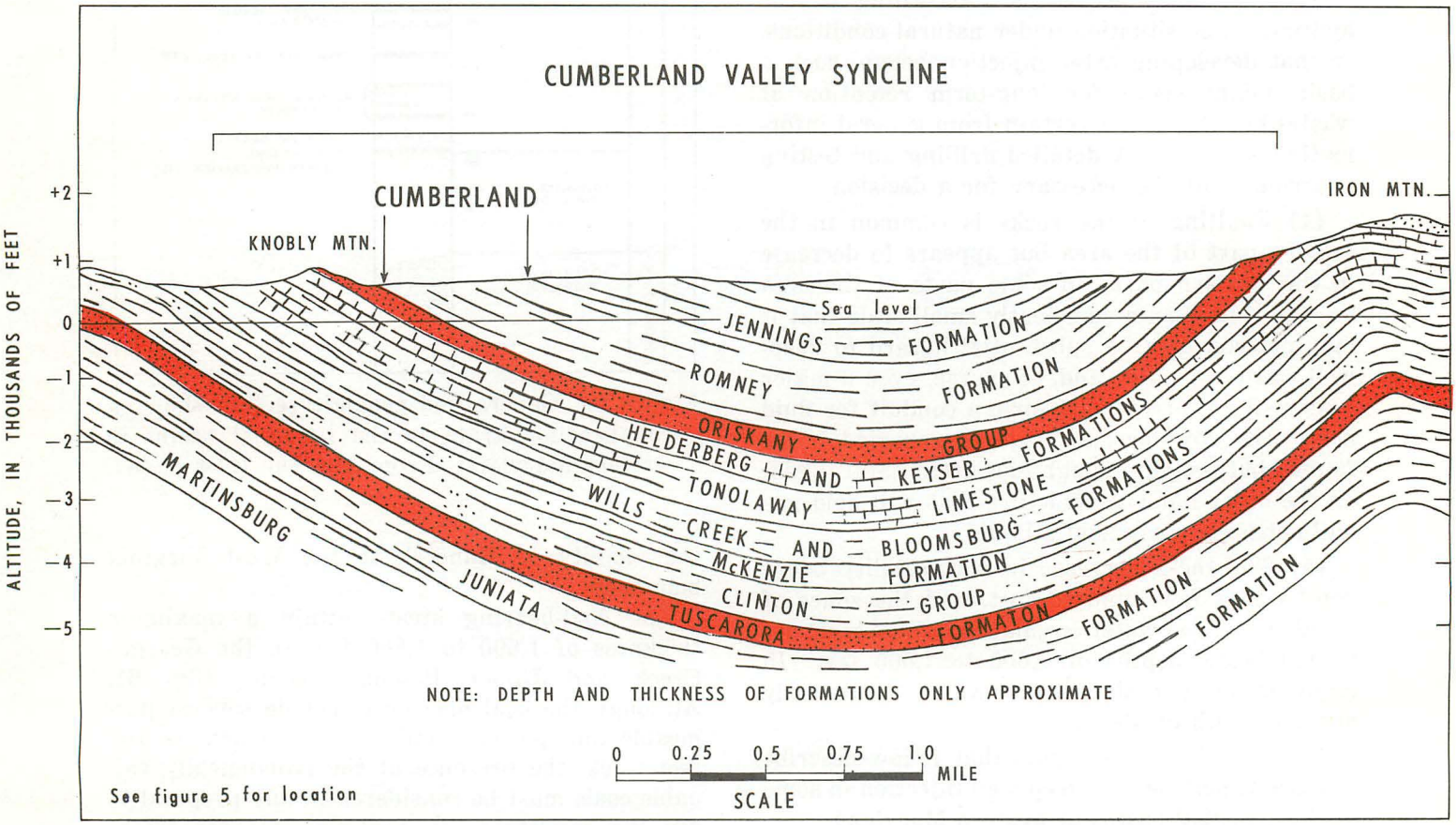

Figure 7. Geologic section across the Cumberland Valley syncline (Modified from Slaughter, 1962).

Table 3. Geologic units near Cumberland and their properties relating to liquid-waste storage
(Adapted from the Geologic Map of Maryland, 1968)

System	Group and Formation		Thickness (feet)	Lithologic character	Properties relating to liquid-waste storage
Devonian	Chemung Formation	Formerly Jennings Formation	60+	Predominantly marine beds characterized by gray to olive-green graywacke, siltstone, and shale.	Not at sufficient depth to enable waste injection at low risk. Porosity of 49 samples from Pennsylvania averages 9.5 percent. 1/
	Parkhead Sandstone	Formerly Jennings Formation	400+	Gray to olive-green sandy shale, conglomeratic sandstone, and graywacke; may be absent near Cumberland.	As above. No porosity or permeability data available.
	Brallier Formation (formerly Woodmont Shale)	Formerly Jennings Formation	1,700 to 2,000	Medium to dark-gray laminated shale and siltstone; grain size coarsens upward.	Strata probably would function chiefly as confining layers below depths of a few hundred feet, but faulting of strata in vicinity of Cumberland may affect the ability of the shales to confine fluids injected into deeper zones. No porosity or permeability data available.
	Harrell Shale	Formerly Jennings Formation	140 to 300	Dark-gray laminated shale; absent east of Cumberland where Brallier lies directly on Mahantango.	
	Mahantango Formation	Formerly Romney Formation	600 to 1,200	Dark-gray laminated shale, siltstone, and very fine grained sandstone.	
	Marcellus Shale	Formerly Romney Formation	250 to 500	Gray-black thinly laminated pyritic, carbonaceous shale.	
	Tioga Metabentonite Bed	Formerly Romney Formation	1+	Brownish-gray thinly laminated shale containing sand-size mica flakes.	
	Needmore Shale	Formerly Romney Formation	70 to 145	Olive-gray to black shale and dark thin-bedded, fossiliferous, argillaceous limestone.	
	Oriskany Group	Ridgeley Sandstone	50 to 160	White medium-to-coarse-grained fossiliferous, calcareous orthoquartzite.	Important gas-producing sand in western Md. and adjacent areas in Pa. and W. Va. Porosity of 33 samples from Oriskany Group in W. Va. ranges from 0 to 10 percent and averages 3.9 percent. 2/ Formations appear physically suitable for waste injection; presence of gas fields locally must be considered.
	Oriskany Group	Shriver Chert	14 to 170	Dark-gray, brown, and black silty shales, cherty shales, and nodular and bedded black chert; fossiliferous.	
	Helderberg Formation		50 to 60	Limestone and calcareous shale; chert common in middle part.	Possible waste-injection zone. No porosity or permeability data available.
	Keyser Limestone		285 to 300	Dark-gray thin to thick-bedded calcarenite; nodular limestone and dolomitic limestone; cherty near top; fossiliferous.	Possible waste-injection zone if sufficiently cavernous. Equivalent strata (Bass Islands Dolomite) used for waste-injection near Erie, Pa.
Silurian	Tonoloway Limestone		550 to 600	Gray thin-bedded limestone and calcareous shale; fossiliferous; locally contains ostracodes.	
	Wills Creek Shale		450 to 600	Olive to yellowish-gray thin-bedded mudstone, calcareous shale, argillaceous limestone, and sandstone.	Strata probably would function chiefly as confining layers. No porosity or permeability data available.
	Bloomsburg Formation		20 to 200	Bright-red hematitic thin- to thick-bedded sandstone and shale.	
	McKenzie Formation		285 to 380	Gray thin-bedded shale and argillaceous limestone; interbedded red sandstone and shale to the east.	
	Clinton Group	Rochester Shale	25 to 40	Gray thin-bedded calcareous shale and dark-gray thin- to medium-bedded lenticular limestone.	
	Clinton Group	Keefer Sandstone	10 to 25	White to yellowish-gray protoquartzite and orthoquartzite, calcareous to the west.	Possible waste-injection zone. No porosity or permeability data available.
	Clinton Group	Rose Hill Formation	300 to 570	Olive-gray to drab thin-bedded shale; some purple shale and gray thin-bedded sandstone.	
	Tuscarora Sandstone		400+	White to light-gray thin- to thick-bedded, cross-stratified subgraywacke and orthoquartzite.	Possible waste-injection zone. Average porosity of 7 samples from W. Va. is 1 percent 3/; average porosity of 19 samples from Pa. ranges from 9 to 19 percent and averages 15 percent. 4/
Ordovician	Juniata Formation		450+	Red to greenish-gray thin- to thick-bedded siltstone, shale, subgraywacke, and protoquartzite; interbedded conglomerate.	Porosity of 6 samples ranges from 9 to 12 percent and averages 10 percent. 4/ Includes strata probably usable for waste storage and others that would serve as confining beds.

1/ From Manger (1962, p. 5), based on well cores from depth of 1,700 to 2,300 feet.

2/ From Heald (1965, p. 10), based on well cores and outcrop samples.

3/ From Manger (1962, p. 5), based on well cores from Wood County deep test well at depth of 7,668 to 7,803 feet.

4/ From Hardaway (1968, p. 123), based on outcrop samples from Bedford County, Pa.

(1970), it is not likely that there will be many proposals for injection of wastes in the synclinal coal basins because of the low level of industrialization in them.

Cumberland Valley Syncline: The towns of Cumberland and South Cumberland, major industrial and commercial centers in western Maryland, lie within the Cumberland Valley syncline. At Cumberland a thick sequence of sandstone, shale, and limestone has been downwarped to form a major syncline, 3 to 4 miles wide (fig. 7). Only detailed study of local hydrodynamic conditions would enable one to predict if this synclinal structure would serve for long-term retention of waste. Permeable horizons most likely to be considered useful for waste storage are: (1) the Oriskany Group (the Ridgeley Sandstone and the Shriver Chert), whose upper surface in the center of the basin is estimated to lie at a depth of 1,500 to 2,000 feet; (2) the Helderberg and Keyser Formations, lying immediately under the Oriskany Group and consisting of porous limestone and dolomitic limestone; and (3) a deeper unit, the Tuscarora Sandstone, lying at an estimated depth of 5,500 to 6,000 feet beneath the center of the syncline.

The geology of an area immediately southeast of Cumberland is well described by de Witt and Colton (1964), and their description of the character of the surface formations and the structural conditions provides a valuable guide for understanding the geology of the Cumberland area.

Table 3, adapted from the explanation of the Geologic Map of Maryland (Maryland Geological Survey, 1968), shows the thickness and lithologic character of the formations of the Cumberland area and their properties relating to liquid-waste storage. In the center of the basin an estimated 1,500 to 2,000 feet of shale and siltstone, comprising the Needmore, Tioga, Marcellus, Mahantango, Harrell, and Brallier Formations, lie above the Oriskany Group. The shale-siltstone sequence might function as an effective confining layer, provided that faults in the vicinity are not large or open enough that injected fluids could migrate upward along the fault planes and mix with overlying potable ground water; the possible effects of pressure injection must be considered in this regard. Figure 8 shows how injected fluids might escape and how wells, springs, and ultimately surface streams might become contaminated by the waste fluids. The driving force necessary to cause the upward migration of the disposed fluid would be the injection pressure necessary to force the fluid into the aquifer at the disposal well, although upward migration of fluids could occur naturally under the appropriate hydrodynamic conditions. As the aquifer receiving the injected fluid is already filled with resident saline water, the resident fluid might appear in an overlying fresh-water aquifer, or in a stream, months or years ahead of the injected fluid. Thus, appearance of saline water at or near the land surface might provide evidence of the otherwise undetected migration of waste fluid from the stratum used for injection.

It is reported that in southwestern Indiana saline water migrated upward along fault zones into overlying fresh-water aquifers owing to a nearby brine-disposal operation. As a result of this contamination abandonment of the water-supply wells was necessitated (Task Committee on Saltwater Intrusion, 1969, p. 1,659).

Little is known of the hydrodynamic conditions in the Cumberland Valley syncline, although inconclusive evidence suggests that the zone of delayed circulation may in places extend to a depth of at least 500 feet. Slaughter (1962, p. 114) reports that fresh water (75 mg/l of dissolved solids) was obtained at a depth of 345 to 366 feet in a 952-foot test hole drilled at the Celanese Corp. plant a few miles south of Cumberland. The same author also reports that a 550-foot well at the Queen City Brewing Co. in downtown Cumberland yielded fresh water (693 mg/l of dissolved solids) from the Helderberg Formation. The water-yielding zone in this well is reported to be at a depth of about 325 feet.

At Ridgeley, West Va., Slaughter (p. 109) reports that water containing 8,300 mg/l of chloride was obtained from a depth of 640 feet in an 1,100-foot test well drilled near the engine terminal of the Western Maryland Railroad. Ridgeley is immediately across the Potomac River from Cumberland and is in the same geologic and topographic basin.

The scanty data suggest that in the Cumberland Valley most ground water below depths of 700 to 1,000 feet is in the lethargic or stagnant zone, but further information is required to appraise this factor more definitively.

Hagerstown Valley

The Hagerstown Valley, known also as the Cumberland Valley in Pennsylvania and the Shenandoah Valley in Virginia, is a broad, gently rolling lowland underlain in the eastern part by a

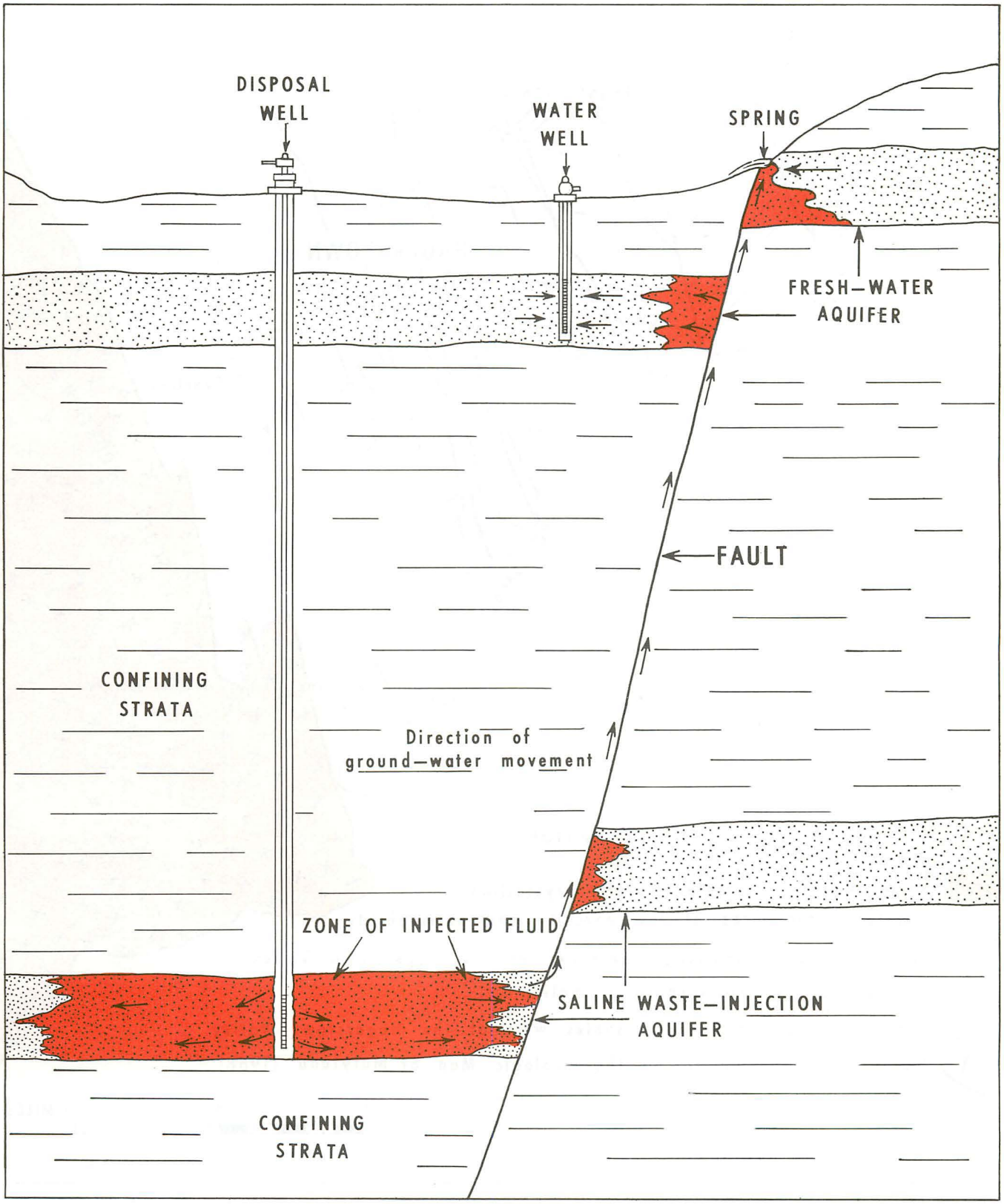

Figure 8. Schematic diagram showing how injected waste fluids might escape along a fault plane and contaminate an overlying fresh-water aquifer.

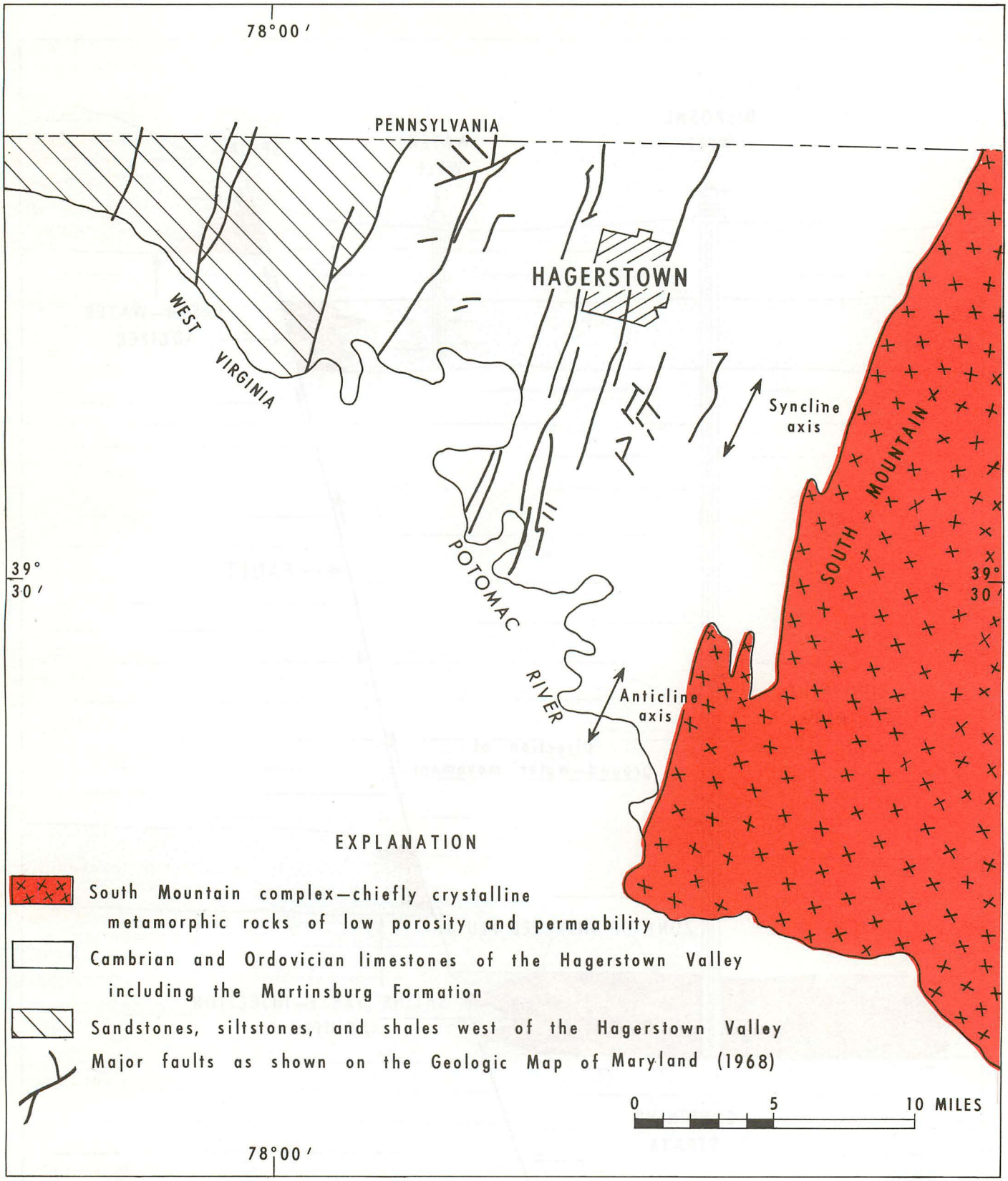

Figure 9. Geologic map of the Hagerstown Valley showing major mapped faults.

thick sequence of limestone of Cambrian and Ordovician age and, in the western part, by shale of Ordovician age. The depth to Precambrian crystalline basement rocks in the valley is estimated to be about 30,000 feet (fig. 1), but, because of the complex folding and faulting of the strata, the total stratigraphic thickness of the rocks is not known for certain; it is probably at least 15,000 feet.

Hagerstown, an important commercial and manufacturing center, had an estimated population of 38,000 in 1965 (Maryland Department of Economic Development, 1967, p. 45). Major geologic and hydrologic considerations with regard to deep-well storage of liquid wastes are:

(1) Although most of the valley is underlain by limestone which in part is cavernous and permeable, the area is structurally complex and many of the beds are highly folded and faulted. This has been illustrated by Slaughter (1962, pl. 4, sec. C-D). The extent of the mapped faulting of the rocks is shown in figure 9, and undoubtedly there are many other faults that have not been recognized in field mapping. Vertical ground-water movement probably occurs along the faults, but the maximum depth at which this occurs is not known.

(2) Some of the limestone strata are sufficiently permeable near the land surface to yield several hundred gallons a minute to individual wells, but others are tight and yield little water to wells. Widespread confining conditions probably do not exist near the surface, and the zones of rapid and delayed ground-water circulation may extend to considerable depths. The depth at which highly mineralized water may be encountered—and, hence, the depth to the lethargic or stagnant zone—is not known but may exceed 2,000 feet. Slaughter (1962, p. 148) reports that water from a 527-foot well (Wa-Dh 11) near Shepherdstown, W. Va., contained 607 mg/1 of dissolved solids, and a 501-foot well (Wa-Bk 9) east of Hagerstown yielded water having a dissolved-solids content of only 200 mg/l. Of course, the waters represented by these analyses may not have come from the bottom of the well, but the analyses indicate that the wells penetrated only the zone of rapid or delayed circulation.

It is likely that the limestone strata are less permeable at great depths where solution by circulating meteoric waters is not effective. The lower permeability would increase the confining properties of the rocks, but at the same time would reduce their ability to accept waste liquids freely. Evidence of a marked decrease in the porosity (and permeability) of limestone at depth is provided by the core analyses of limestone from a deep test well in Wood County, W. Va. (Robertson, 1959, p. 125-126). At a depth of more than 10,000 feet 56 cores from strata equivalent to the Beekmantown Group had a porosity averaging only 0.4 percent. Strata of equivalent age from outcrops in Centre County, Pa., had a porosity range of 2 to 12 percent (Folk, 1948, p. 52).

Table 4 shows the thickness and lithologic character of the formations beneath the Hagerstown Valley and their properties relating to liquid-waste injection. Because the permeability of the rocks appears to decrease downward and because there is a general absence of suitable confining layers at shallow depths, there likely are few places in the Hagerstown Valley where liquid wastes can be injected and stored satisfactorily.

PIEDMONT REGION

Catoctin Mountain Belt

The Catoctin Mountain belt of this report includes the area lying north of the Potomac River and south of the Pennsylvania line, bordered on the west by the Hagerstown Valley and on the east by the Frederick Valley and the Triassic lowlands. The area is underlain by very ancient, highly metamorphosed, Precambrian crystalline rocks consisting of metabasalt, metarhyolite, granodiorite, and granite gneiss. The rocks are fractured and creviced, at least in the uppermost few hundred feet. Depth of weathering in the valleys ranges up to as much as 100 feet, but on the average is about 30 feet. On the steeper mountain slopes and sides much of the weathered rock has been removed by erosion. The altitudes in the subregion range from 250 feet along the Potomac River to about 2,100 feet at the top of South Mountain near the Pennsylvania line.

Ground water occurs chiefly in permeable zones at the base of the decomposed rock and in fractures below the top of the zone of saturation. The porosity and permeability of the fresh, unaltered rock is extremely low, porosity usually being less than 1 percent.

Most drilled wells yield at least small supplies of ground water in the depth interval from 50 to 200 feet and a few wells yield no water at all even when drilled to greater depths. Meyer (p. 65) reports that about 18 percent of the wells drilled

Table 4. Geologic units in the Hagerstown Valley and their properties relating to liquid-waste storage (Adapted from the Geologic Map of Maryland, 1968).

System	Group and Formation		Thickness (feet)	Lithologic character	Properties relating to liquid-waste storage
Ordovician	Martinsburg Formation		2,000 to 2,500	Upper part interbedded graywacke, siltstone, and shale; lower part brown, gray, and black thin-bedded fissile shale.	Probably would function chiefly as a confining layer where it lies at depth. Porosity of 1 sample of slate from Pennsylvania was 1 percent. 1/
	Chambersburg Limestone		225 to 250	Dark-gray fine-to-medium grained thin-bedded argillaceous limestone.	May contain vugular and intergranular porosity; possible injection zone where it lies at depth. Porosity of 42 cores from equivalent strata (Black River) in West Virginia ranged from 0.1 to 2.7 percent and averaged 0.5 percent. 2/
	St. Paul Group	New Market Limestone	285 to 700	Upper part gray thick-bedded calcilutite; lower part light-gray thin-bedded laminated argillaceous calcilutite.	May contain vugular and intergranular porosity; possible injection zone where it lies at depth. No porosity or permeability data available.
		Row Park Limestone	100 to 680	Light-gray fine-grained medium- to thick-bedded calcarenite; calcilutite and dolomitic limestone; interbedded dark-gray cherty granular limestone.	
	Beekmantown Group	Pinesburg Station Dolomite	375 to 500	Light-gray laminated and mottled cherty dolomite; nonfossiliferous.	May contain vugular and intergranular porosity, but apparently confining strata are absent immediately above and below the Beekmantown. Porosity of 56 cores from West Virginia ranged from 0.1 to 1.1 percent and averaged 0.4 percent. 2/ Porosity of equivalent exposed strata in Pennsylvania (Nittany Dolomite) ranged from 2 to 12 percent. 4/
		Rockdale Run Formation	1,700 to 2,500	Upper third gray, mottled cherty dolomite and dolomitic limestone; Lower two-thirds gray cherty argillaceous calcarenite and algal limestone with inter-bedded dolomite and oolitic limestone.	
		Stonehenge Limestone	500 to 800	Upper part gray thin-bedded coarse-grained to conglomeratic, oolitic calcarenite; some dolomite; lower part gray thick-bedded fine-grained algal limestone.	
?	Conococheague Limestone		1,600 to 1,900	Dark-blue laminated, oolitic, argillaceous, and siliceous limestone, algal limestone, and flat-pebble conglomerate; siliceous shale partings; some sandstone and dolomite.	Possible injection zone where it lies at depth, if overlain by adequate confining layer. No porosity or permeability data available.
Cambrian	Elbrook Limestone		1,400 to 3,000±	Light-blue laminated, argillaceous limestone and calcareous shale; some dolomite.	
	Waynesboro Formation		600+	Upper part red, gray, and yellowish-brown thin-bedded siltstone, shale, and ripple-marked, crossbedded sandstone; lower part interbedded dark-gray to red shale and thin-bedded dolomite.	Possible injection zone in upper part, if overlain by adequate confining layer. No porosity or permeability data available.
	Tomstown Dolomite		200 to 1,000	Interbedded light-gray to yellowish-gray thin-to-thick-bedded dolomite and limestone; some shale layers; contact with underlying formation gradational at base.	Possibly contains vugular porosity. No porosity or permeability data available.

1/ From Windes (1949, p. 9); sample from Northampton County, Pa.
2/ From Robertson (1959, p. 124-125); cores from depths of 9,416 to 10,511 feet, Wood County, W. Va., deep test well.
3/ From Robertson (1959, p. 125-126); cores from depths of 10,531 to 11,945 feet, Wood County, deep test.
4/ From Folk (1948, p. 52); based on a large number of outcrop samples from Centre County, Pa.

in the Catoctin Metabasalt yield less than 5 gpm. No highly mineralized water has been reported from any wells or springs in the Catoctin Mountain belt, although very few wells have been drilled to depths in excess of 300 feet. However, Meyer (p. 72) reports that a 1,000-foot well (Fr-Bd 28) drilled into quartzite near Thurmont, Md. yielded a small supply of fresh water. The same author also reports that a well a few miles south of Bd 28 was drilled in phyllite to a depth of 1,140 feet, but no mention is made of the quality of water obtained.

In summary, wastes injected into the rocks of the Catoctin Mountain subregion by means of deep wells would likely escape from the intended storage zone because of the highly metamorphosed and fractured character of the rocks, their complex geology, and the probable absence of an effective confining layer overlying a zone sufficiently permeable to store and transmit water.

Frederick Valley and Triassic Lowlands

The Frederick Valley is a 3- to 5-mile-wide lowland east of Catoctin Mountain and west of the main Piedmont area. The valley extends southward across the Potomac River into Virginia and northward about 23 miles from the river. It is drained chiefly by the Monocacy River, whose headwaters are in Pennsylvania. The terrain is gently undulating to flat, and the valley is underlain mainly by limestone and dolomite of Cambrian and Ordovician age.

The carbonate rocks have been subdivided into three formational units, the Frederick Limestone, Grove Limestone, and Tomstown Dolomite. The total stratigraphic thickness of these units is on the order of 1,300 feet, and they are underlain at depth by metamorphosed Precambrian rocks.

The rocks of the Frederick Valley are complexly folded into a large syncline, bounded on the west by a major fault (Stose and Stose, 1946, p. 89) known as the Triassic border fault and on the east by a series of unnamed smaller faults. Several prominent faults trending across the valley are shown on the geologic map of Frederick County (Stose and Stose, 1938). Undoubtedly, many other, smaller faults have not been mapped. The dip of the strata range from 10° to 50° or more, and the strike is north to northeast.

The carbonate rocks of the valley are moderately good aquifers, chiefly as a result of solutional development of their uppermost few hundred feet. Meyer (1958, p. 78) reports that the yields of wells in the rocks range from a few gallons per minute to a maximum of 275 gpm. The depths of water wells are commonly in the range of 100 to 300 feet. The deepest well, 1,209 feet, is at a cannery at Adamstown, about 8 miles south of Frederick. Unfortunately, no log of the well is available, but apparently most of the water yielded by it comes from a depth of less than 450 feet.

Little information is available concerning the hydrologic properties of the carbonate rocks at depths of 500 feet or more, but in places the rocks may be permeable enough to function as aquifers and in other places may be sufficiently impermeable to function as confining layers. Hydrodynamic conditions in the valley are complex and poorly understood. No saline ground water has been reported, and it is likely that the zone of rapid circulation extends to depths of hundreds of feet.

Stose and Stose (1946, p. 44) report that a 50-foot stratum of black to gray shale occurs near the bottom of the Frederick Limestone. However, because of the variable dip of the rocks and the numerous faults in the area, the ability of the shale layer to confine fluids effectively is doubtful.

Therefore, because of widespread faulting, structural disturbance of the strata, and because extensive confining layers are absent, the risk of deep-well waste injection appears to be significantly high in the Frederick Valley.

A thick sequence of red shale, siltstone, and sandstone of Triassic age overlies older schist, phyllite, and limestone in northwestern Carroll and northeastern Frederick Counties. The Triassic sedimentary rocks extend southward along a narrow band to the Potomac River, where they widen again and extend southeastward into western Montgomery County (fig. 4). Northwest of Frederick, the Triassic rocks overlie the Frederick and Grove Limestones along a band 5 to 15 miles wide. Southwest of Frederick, the band in which the limestones underlie the Triassic narrows in places to less than a mile in width.

The Triassic rocks have been grouped into two formations, the basal New Oxford Formation and the overlying Gettysburg Shale. The New Oxford consists chiefly of red to purplish sandstone and shale and beds of light-gray to greenish-yellow arkosic sandstone. A basal limestone conglomerate is composed of coarse and fine pebbles of white and gray limestone of Paleozoic age and scattered quartz pebbles in a matrix of gray to red shaly limestone. This unit can be cut and

polished and has been used as an ornamental stone, known as "Potomac marble." The thickness of the conglomerate is not known for certain, but in outcrops it may range from 20 to 50 feet. The total thickness of the New Oxford is estimated to be 4,500 feet near the Pennsylvania State line, but the formation may thin to the south.

The Gettysburg Shale consists of red and green shale, siltstone, and some red sandstone. The total thickness of the Gettysburg is estimated to be about 5,000 feet near the Pennsylvania line, but the formation thins to the south toward Virginia. Roberts (1928, p. 91) estimates that the entire thickness of Triassic rocks in Virginia is 1,000 to 1,500 feet.

The carbonate rocks, the Triassic rocks, and the crystalline rocks of the Piedmont have been intruded by a series of diabase dikes and sills, which extend to great but unknown depths. The contact of the diabase and the adjacent Triassic rocks is characterized by a "baked" zone of purple to black shale and siltstone. The rocks in the baked zone appear to be somewhat more permeable than they do away from this zone.

Hydrodynamic conditions in the rocks of Triassic age are variable, and the depths of the zones of rapid and delayed circulation may range widely. The sandstone strata in the New Oxford Formation appear to have little interstitial permeability, and most of the ground water in them moves in fractures. In Maryland the most productive well penetrating fractured sandstone strata of Triassic age yields a total of 300 gpm from two zones, at depths of 200-215 and 415-438 feet. This well, at Taneytown in Carroll County, was completed in 1967 to a total depth of 600 feet. Thus, fresh water is present at this locality to a depth of at least 438 feet.

Not all wells in the Triassic rocks are productive of even domestic supplies of ground water. Meyer (1958, p. 125) reports that nine wells in the Gettysburg Shale in Frederick County yielded an average of only 1.5 gpm. These data indicate that these rocks are relatively impervious, at least locally, and that in some places deep circulation of meteroic waters may be retarded or essentially lacking.

Wood and Johnston (1964, p. 44) report that fresh water having a dissolved-solids content of 350± mg/l was obtained from the uppermost 500 feet in a 910-foot well drilled into rocks of Triassic age at East Berlin in Adams County, Pa.

Data of significance in regard to ground-water circulation in the Triassic rocks are reported from Loudoun County, Va., by Johnston (1960, p. 2). In 1955 a 1,005-foot well was drilled on the east rim of a diabase body near Herndon, about 20 miles west of Washington, D.C. This well yielded a small quantity of moderately saline water from the bottom of the hole. Because of the unusual chemical character of the water (high in calcium chloride) the analysis is given below:

Constituent	Concentration (mg/l except for pH)
Silica (SiO_2)	11
Aluminum (Al)	.2
Iron (Fe)	3.4
Calcium (Ca)	1,860
Magnesium (Mg)	42
Sodium (Na)	777
Potassium (K)	2.7
Lithium (Li)	11
Bicarbonate (HCO_3)	1.8
Carbonate (CO_3)	7.9
Sulfate (SO_4)	177
Chloride (Cl)	4,500
Fluoride (F)	.0
Nitrate (NO_3)	3.6
Phosphate (PO_4)	.1
Dissolved solids	7,390
Hardness as $CaCO_3$	4,810
Noncarbonate hardness as $CaCO_3$	4,800
pH	9.0

The analysis of this water suggests that the well may have penetrated the zone of lethargic circulation. There is no information on the extent of occurrence of water of this character in the deeper Triassic rocks.

The data available indicate that the zone of lethargic circulation in the Triassic rocks may lie at a depth of 1,000 feet or more. The rocks are faulted in many places, but the effect of the faulting on ground-water circulation is not known. The existence of several really extensive diabase sills and dikes may permit vertical circulation of ground water along the contacts and across the bedding planes of shales and similar impervious strata, even though the diabase itself is of generally low permeability. Therefore, the possibilities of confining injected fluids in the rocks of Triassic age are doubtful.

Central and Eastern Piedmont

The central and eastern Piedmont area, as defined in this report, includes that part of Maryland in which the land surface is underlain by crystalline igneous and metamorphic rocks or their weathering products. It extends west of the Fall Zone to the Frederick Valley and the Triassic lowland area (fig. 4).

The Piedmont is underlain by a complex series of metamorphosed rocks including gneiss, slate, phyllite, schist, marble, and granitic and gabbroic rocks. The region is characterized by gently undulating to hilly and mountainous topography. The relief is on the order of 1,200 feet, ranging from sea level at the mouth of the Susquehanna River to the maximum at the top of Sugarloaf Mountain. The rocks are weathered and decomposed to depths as great as 100 feet and locally more, but the average depth of weathering is on the order of 40 to 50 feet (Cleaves, 1968, p. 5).

Ground water occurs in the weathered rock (saprolite) and in numerous fractures and openings along planes of schistosity in the unweathered rocks. Below depths of a few hundred feet the fractures and other planar openings generally decrease in size and extent. In general, few water-bearing fractures exist below a depth of 500 to 1,000 feet. At these depths the rocks are virtually impervious, although a few major fractures may extend to depths greater than 1,000 feet. The porosity of the unfractured and unweathered crystalline rocks is commonly less than 1 percent, as shown in table 5, based on mine and

Table 5. Apparent porosity of various types of crystalline rocks[1]

Rock type	Locality	Apparent porosity[2] (percent)
Granite	Maryland	0.8
Do.	Nevada	.9
Do.	North Carolina	.7
Do. (core parallel to foliation)	do.	.7
Granite gneiss and syenite	New York	.8
Do.	do.	.7
Do.	do.	.9
Gabbro (altered)	do.	.3
Pegmatite	do.	1.1
Diabase and metabasalt (altered)	do.	.3
Diabase (coarse-grained)	Michigan	1.2
Do. (fine-grained)	do.	1.0
Do.	do.	.5
Do.	do.	.6
Greenstone	Virginia	.7
Do.	do.	.5
Greenstone, schistose	Michigan	.6
Greenstone and phyllite	do.	.4
Phyllite, green	do.	1.1
Marble	New York	1.8
Do.	Maryland	.6
Average, 21 cores	—	0.8

[1] From Windes (1949, Part I, p. 8-13).
[2] Apparent porosity (P_a) based on the formula

$$P_a = \frac{(\text{Wet weight—Dry weight})\ 100}{\text{Density of } H_2O \times \text{Volume of specimen}}$$

quarry rock analyses by the U.S. Bureau of Mines from various places in the United States.

Although numerous aquifer tests of the crystalline rocks in Maryland have been made (Dingman and Ferguson, 1956; Nutter and Otton, 1969), the hydraulic properties (coefficients of transmissibility and storage) determined from these tests are generally applicable only to the uppermost few hundred feet of the rocks. Little is known of the hydraulic properties of these rocks at depths below a few hundred feet, although Christl (1964, p. 27) provides some significant permeability and porosity values at depths of about 1,200 to 1,900 feet in gneiss and schist in South Carolina. He indicates that the coefficient of permeability of the unfractured rock averages about 0.002 gpd per ft^2 (gallons per day per square foot) and the porosity is about 0.01 percent, a value well below that reported for the mine and quarry rocks. However, Christl reports the coefficient of permeability of the fractured zone in the rocks to be about 1.0 gpd per ft^2 and the porosity, about 1 percent.

Hydrodynamic conditions in the Piedmont area are such that nearly all the ground water in the crystalline rocks moves in the zone of rapid or delayed circulation. However, Christl (p. 25) indicates that the small quantities of water obtained from fractures in crystalline rocks in South Carolina below a depth of 1,000 feet had a dissolved-solids content ranging from 2,500 to 7,100 mg/l. These waters are high in sodium and sulfate and also contained dissolved gases in amounts ranging up to 25 ml/l (milliliters per liter). The gases had anomalously high concentrations of helium and low concentrations of oxygen and carbon dioxide. The mineralization of this water and the presence of helium indicates very sluggish water circulation. No water of this character is known from deep wells in Maryland, but its occurrence is not improbable.

In summary, because their permeability and porosity are low and decrease downward, so that an extensive confining zone is not present above permeable rock, and because of extensive fracturing and faulting, the crystalline rocks of the central and eastern Piedmont offer little or no opportunity for successful storage and containment of liquid wastes. It is highly probable that injected wastes would migrate laterally and vertically along fractures and ultimately enter streams or fresh-water zones near the surface.

COASTAL PLAIN REGION

The Coastal Plain region, comprising somewhat more than half the total area of Maryland, is underlain by a series of layers of unconsolidated sand and gravel, silty sand, clay, marl, and shell beds, superimposed upon the buried eastward continuation of the crystalline rocks of the Piedmont. The beds dip and thicken to the southeast and east and thus form a wedge whose northwest edge lies along the Fall Zone. Along the Atlantic Coast, near Ocean City, the total thickness of the wedge is nearly 10,000 feet and it decreases southward to 8,000 to 9,000 feet at the Virginia State line on Assateague Island.

The major physiographic feature of the Maryland Coastal Plain is the Chesapeake Bay, the drowned valley of the lower Susquehanna River, which bisects the Coastal Plain into an eastern and a western part. Although the relief of the Coastal Plain is as great as 200 feet in central Prince Georges County in the western part, much of the area in the eastern part has altitudes of less than 50 feet and a local relief of less than 20 feet. The region contains much fertile, productive farmland and supports a thriving seafood industry, lumbering, and some other small industries.

Inner Coastal Plain

In this report the Inner Coastal Plain subregion is designated as that part of the Coastal Plain region where the unconsolidated sediments range in thickness from 0 to about 2,000 feet (figs. 1 and 4). Several important fresh-water aquifers underlie the area, and ground water is an important source of supply for many towns, numerous industries, and Government installations. Additionally, thousands of domestic wells obtain water from these aquifers.

Fresh water occurs at depths of more than 1,000 feet in several places, as indicated by chemical analyses of water from wells. A well at Annapolis (AA-De 92) screened in the Patuxent Formation (Cretaceous System) at depths of 950 to 1,030 feet yields water having a dissolved-solids content of less than 200 mg/l and a chloride content of less than 1 mg/l. A well at Morgantown in southern Charles County yields water having a dissolved-solids content of 376 to 394 mg/l and a chloride content of 25 to 29 mg/l. This well also is screened in the Patuxent Formation, at a depth

of 1,080 to 1,095 feet. Mack (1966, p. 96) reports that water from a depth of about 1,300 feet in well PG-Fc 17, drilled in connection with a planned gas-storage project in central Prince Georges County, had 844 mg/l of dissolved solids and a chloride content of 332 mg/l. This water was from the so-called "Terminus" sand in the Patuxent Formation.

Except for the Baltimore industrial area, where extensive salt-water contamination of the aquifers has resulted from heavy pumping and from dredging of the Patapsco River estuary, saline water has not been reported from aquifers in the Inner Coastal Plain, although Clark, Mathews, and Berry (1918, p. 270-271) report that "very salty" water was obtained at a depth of 1,135 feet from a well at Chestertown in Kent County. Well QA-Be 15 drilled at Kingstown in adjacent Queen Annes County encountered waters containing 4,180 mg/l of dissolved solids and 2,580 mg/l of chlorides at a depth of 1,357 to 1,367 feet.

Apparently, most aquifers in the Inner Coastal Plain contain fresh water, at least to depths of about 1,000 to 1,300 feet. Although no chemical analyses are available for aquifers in the depth range of 1,500 to 2,000 feet, it is presumed that the zone of delayed circulation extends to these depths and the water contains not more than a few thousand milligrams per liter of dissolved solids. Because of the relatively shallow depths involved and the resulting uncertainty of confining conditions, and because of the presence of fresh or only slightly or moderately saline water in most of the aquifers, subsurface waste storage presents a very significant hazard to ground-water supplies in the Inner Coastal Plain.

Middle Coastal Plain

The Middle Coastal Plain, as defined in this report, extends across a belt about 45 miles wide, where the unconsolidated sedimentary deposits range in thickness from 2,000 to about 4,500 feet (fig. 1). Several fresh-water aquifers occur throughout the area, and ground water is the only source of supply for nearly all municipal, industrial, commercial, and domestic users.

The depths of wells in the area range from a few feet to more than 1,500 feet, but most of the aquifers in current use (1969) lie above a depth of 1,000 feet. The maximum depth of occurrence of fresh water is not known throughout most of the area, but in some places it lies below 1,400 feet. Rasmussen and Slaughter (1957, p. 131) report that water containing 124 to 134 mg/l of dissolved solids was obtained from a sand at a depth of 1,350-1,420 feet in well Tal-Cb 89 at Wades Point in northwestern Talbot County. Well Tal-Cb 89 was drilled to a total depth of 1,520 feet, and crystalline basement rock is estimated to lie 500 to 800 feet deeper. Probably one or more water-yielding sands are present in the unexplored interval, but it is not known if these deeper sands contain fresh water. Possibly slighty saline water (1,000 to 3,000 mg/l) is present in them at Wades Point.

In 1965 an exploratory test hole was drilled to a depth of 1,505 feet near Cambridge in Dorchester County. Although water samples were not obtained from strata penetrated by this well, electric and gamma-ray logs were made (Hansen, 1968, pl. 6). Analysis of these logs suggests that two sands in the depth interval of 1,270 to 1,400 feet probably contain fresh water.

The Magothy Formation, at a depth of 900 to 925 feet below sea level, has supplied fresh water to Cambridge since 1949, when the first wells were placed in use (Rasmussen and Slaughter, 1957, p. 95). The Magothy yields fresh water also at Easton, about 15 miles north of Cambridge, from a municipal well at a depth of about 1,100 feet. The total thickness of Coastal Plain sediments at Cambridge is estimated to be 3,000 feet; therefore, if water or even slight or moderate salinity is present, it probably is in the depth interval of 1,500 to 3,000 feet.

The distribution and depth of occurrence of fresh and salt water in the aquifers in the Middle Costal Plain is somewhat complex, as it appears that in some places fresh-water aquifers underlie aquifers containing saline water. For example, Rasmussen and Slaughter (1957, p. 130) report that a 315-foot well in the Calvert Formation (Miocene Series) near Vienna (Dorchester County) yielded water having a dissolved-solids content of 3,000 to 4,300 mg/l. These authors (p. 130) report also that a 406-foot well in the Piney Point Formation at Fishing Creek yielded water having a chloride content of 2,080 mg/l. It is possible that these analyses are of water from wells contaminated by downward leakage of saline surface water along the outside of inadequately sealed casings. If this is correct, then the analyses are not representative of the formation water. However, the Calvert Formation is reported to yield saline water at other places in Dorchester County.

It is possible that, at depths below about 2,000 feet, there are saline aquifers separated from the fresh-water section above by thick, extensive clay beds which would function as effective confining layers. Only additional information on the regional subsurface geology and detailed test drilling and well testing in specific areas would indicate the possibilities that these saline aquifers might be considered potential targets for waste injection. One factor to be considered is the possible updip migration of injected fluids that are lighter than the native water. This factor of course would be most significant along the northwestern, or updip, edge of the Middle Coastal Plain.

Because of the greater thickness of strata (as much as 4,500 feet) and the likely existence of saline aquifers below a depth of 2,000 feet, the hazards of subsurface waste storage tend to decrease from the inner Coastal Plain through the Middle Coastal Plain. Nevertheless, there is considerable risk to the hydrologic environment in the Middle Coastal Plain; hence, any proposal to use the deeper strata for liquid waste storage should be accompanied by adequate exploration, test drilling, and a detailed local site study.

Outer Coastal Plain

The Outer Coastal Plain is restricted to that part of the Coastal Plain province where the unconsolidated sediments exceed 4,500 feet in thickness (fig. 1). The western boundary of the area coincides roughly with the Nanticoke River, and the eastern boundary is the Atlantic Ocean. Water from drilled, driven, and dug wells furnishes nearly all the water used for municipal, domestic, industrial, and irrigation use. Several aquifers are present, but the largest supplies of water have been obtained from the deposits of Pleistocene age at depths generally less than 100 feet.

The occurrence of fresh water in the aquifers is somewhat erratic, and only in the southeastern part of Somerset County near the town of Crisfield and on the low islands of the Chesapeake Bay has fresh water been obtained below a depth of 1,000 feet. Hansen (1967, p. 13) reports that fresh water having a dissolved-solids content of 751 mg/l is obtained from a well at the Janes Island State Park near Crisfield. This well is screened opposite the Raritan Formation at a depth of 1,272 to 1,287 feet. The overlying Magothy Formation, at a depth of 1,128 to 1,138 feet, also yields fresh water (620 mg/l of dissolved solids) at Janes Island. However, Rasmussen and Slaughter (1955, p. 202) report that in the Crisfield area a 362-foot well in the Choptank Formation (Miocene Series) yielded water having a dissolved-solids content of 3,440 mg/l and a chloride content of 1,360 mg/l. Water of similar chemical character from a nearby well in the same aquifer is reported by Hansen (1967, p. 7). Apparently, near Crisfield moderately saline water overlies fresh water; and, undoubtedly, saline water underlies Crisfield at some depth greater than 1,300 feet, the approximate depth of the deepest aquifer for which chemical data are available.

North and east of Crisfield fresh water has not been found at depths similar to those at Janes Island. At Pocomoke City (Worcester County) water obtained from a depth of 485-496 feet was reported to be "quite highly mineralized" (Clark, Mathews, and Berry, 1918, p. 326). Fresh-water supplies at Pocomoke City are obtained from a shallower aquifer (Miocene Series) in the depth range of 100 to 150 feet.

Clark, Mathews, and Berry (1918, p. 138) report that at Parsonsburg in Wicomico County "highly mineralized water" was obtained at depths of 755-760 and 940-945 feet in an oil and gas test well drilled about 1917. These same authors report (p. 327) that a 1,706-foot oil and gas test well on the Isle of Wight near Ocean City (Worcester County) yielded water from a stratum of Eocene age having a chloride content of 2,500 mg/l. This water had an estimated dissolved-solids content of about 5,400 mg/l. Chemical analysis of the water from a sand of Miocene age at a depth of 708 feet in a test well drilled in 1969 a few hundred yards south of the Delaware line at North Ocean City indicated that the dissolved solids were 5,240 mg/l and the chloride content was 2,710 mg/l. Slaughter (1962, p. T9) says that at Bishopville (Worcester County) water reported to be salty was obtained from a depth of 640 feet in a well penetrating the Choptank Formation (Miocene Series).

Large supplies of fresh ground water are obtained at Ocean City from wells ranging in depth from about 100 to 300 feet. The wells tap the Pocomoke and Manokin aquifers in the Yorktown Formation (Miocene Series).

In general, in the eastern two-thirds of the Outer Coastal Plain fresh water is not known to occur in the aquifers below a depth of about 500 feet (shaded area in fig. 4) and in the depth interval of 500 to about 1,700 feet saline water is reported at Bishopville, Parsonsburg, North Ocean City, and Pocomoke City.

Table 6. Geologic units near Salisbury and their properties relating to liquid-waste storage
(Modified from the Geologic map of Maryland, 1968)

System and Series			Group and Formation	Thickness (feet)	Lithologic character	Properties relating to liquid-waste storage
Quaternary	Pleistocene	Columbia Group	Parsonsburg, Walston, and Salisbury Formations 1/	50-230	Gravel, sand, silt, and clay; sands crossbedded, poorly sorted, medium to coarse grained, white, red, and yellow; clays silty, gray to bluish gray.	Sand and gravel yield large supplies of fresh ground water throughout an extensive area. Not usable for waste storage if fresh water is to be protected.
Tertiary	Miocene	Yorktown Formation 1/		180-225	Yellowish-white to gray fine- to medium-grained sand, sands locally black or green; gray to bluish-gray clayey silt and granule gravel; present only in the subsurface.	Contains a 40- to 60-foot thick sand, the Manokin aquifer, which in places yields water high in iron content. Another sand, the Pocomoke aquifer, lies above the Manokin separated from it by clay. Entire formation functions chiefly as a semiconfining layer, but lies within the fresh-water section.
		Chesapeake Group	St. Marys Formation	40-60	Clay and sandy clay, greenish-blue to gray, with shells.	Functions chiefly as a confining layer, but may lie in the fresh-water section.
			Choptank Formation	60-120	Clay, silty, green and gray, with shells; some sand, gray, very fine grained; some diatoms.	Probably functions chiefly as a confining layer.
			Calvert Formation	500-550	Clay, silt, sand, and shell layers, diatomaceous, bluish-gray to gray; basal part contains a moderately thick clay layer.	Probably functions chiefly as a confining layer, but contains in its upper part a 40- to 60-foot shell and sand layer, the Nanticoke aquifer; "highly mineralized" water reported from the Calvert(?) at depths of 755-60 feet a few miles east of Salisbury.
	Paleocene and Eocene	Piney Point and Aquia Formations 2/		200-220	Clay, silt, and sand, dark-gray to green.	Chiefly a confining layer, but probably contains a thin saline-water aquifer near top; water-yielding properties unknown.
	Upper	Monmouth, Matawan, Magothy, and Raritan Formations		950+	Clay, sandy and silty clay, and sand layers; clays brown to brownish black and gray at base, grading upward to grayish green; sands 20 to 50 feet thick, lignitic, gray to white.	Several saline-water sands present in interval; hydraulic properties unknown; intervening clays probably function as confining layers.
	?	Arundel and Patapsco Formations		2,100+	Clay, shale, silty shale, and sand, fine to medium; shales are brown, lead gray, and mottled red and green; sands white, gray to olive green; shale pebble zones common; a few sands are 60-80 feet thick.	Sands should yield saline water; hydraulic properties unknown; clays and shales should function as confining layers.
	Lower	Patuxent Formation		930+	Sands, fine to very coarse, white, arkosic, poorly sorted; and shales, sandy, gray, brown and green; carbonaceous matter common; strata sandier than overlying units.	Sands should yield saline water; hydraulic properties unknown but permeability may be high locally; some clays near top probably function as confining layers.
Triassic(?)		Newark(?) Group		135	Shale, hard, red-brown and apple-green; shale, sandy; sandstone, medium- to coarse-grained, arkosic; 30-foot indurated quartz conglomerate at top.	Strata probably function as confining layers; hydraulic properties unknown--if water bearing, would yield only saline water.
Precambrian		Unnamed		70+	Biotite-rich quartzite or mica gneiss; weathered zone 31 feet thick.	Hydraulic properties unknown; might yield very small quantities of saline water.

1/ Information in part from Boggess and Heidel (1968, p. 8-9).

2/ Data for pre-Miocene strata from Anderson and others (1948, fig. 10).

In the western one-third of the area, including Crisfield, Janes Island State Park, and Deal Island, fresh water occurs in aquifers to a depth of about 1,300 feet beneath shallower aquifers containing water of higher salinity. Saline water, containing more than 1,000 mg/l chloride, was obtained from a 362-foot well south of Crisfield. Water of a similar character in relatively shallow strata has been reported at several places along Tangier Sound and up the Nanticoke River as far north as Vienna, Md.

Most of the information concerning the character of the deeper strata in the Outer Coastal Plain is obtained from the records and logs of three deep oil tests drilled during the 1940's near the towns of Salisbury, Berlin, and Ocean City. The geology at these wells, which were drilled to depths of 5,568, 7,178, and 7,710 feet, respectively, is described comprehensively by Anderson and others (1948). Of the three wells, nearly continuous cores were obtained only from the L. G. Hammond No. 1 near Salisbury. These cores extend from a depth of 1,000 feet to the bottom of the well at 5,568 feet. Examination of figure 10 of Anderson's report, a detailed lithologic and electric log of the Hammond well, shows that several sands occur in the depth interval of 2,000 to 5,500 feet. The sands, of Cretaceous age, are separated by clayey layers and, if the sands are sufficiently permeable, may be usable for waste storage—on the assumption that the intervening clay beds are thick, continuous, and extensive. No information is available on this point, or on the hydraulic properties of the sand beds.

Although no water samples were obtained from sands in the Hammond well, Anderson (p. 71) states in regard to the electric log: "In the upper portion of the hole, up to approximately 2,200 feet, the sands all show a low resistance both on the first and second resistance curves. Infiltration is not important in this part of the section, and the fluid content of the sands is either salty or brackish water."

Table 6 summarizes the geologic units near Salisbury and describes their properties relating to liquid waste injection.

No information is available concerning hydrodynamic conditions in the deep aquifers of the area, but hydraulic heads are probably sufficient to cause wells to flow, at least at low altitudes. The water in the deep strata, because of its high mineral content, is denser than fresh water, but may be less dense than normal sea water.

The situation involving the lowest risk with regard to confinement of injected liquid wastes might be a geologic environment similar to that shown in figure 10, where a hypothetical permeable aquifer extends beneath the sea but wedges out in the updip, or landward, direction, thus preventing updip migration of the injected fluid and possible mixing with fresh water at shallower depth.

Such an aquifer, if it were 50 feet thick and extended throughout an area of only a few tens of square miles, might appear to have an enormous potential for waste storage. An aquifer of this character, having a porosity of 20 percent, would appear to be capable of storing about 2 billion gallons (2.079×10^9) of fluid per square mile. However, as the potential injection zone would be filled naturally with saline water, the volume of waste fluid that could be injected is limited to that achieved by compression of the injected and indigenous fluids and dilation of the rock matrix comprising the aquifer, plus that resulting from expulsion of native water from the aquifer.

The compression-dilation term is related to the storage coefficient, expressing the volume of water removed from or accepted by an aquifer when the head is lowered or increased. The coefficient in artesian aquifers such as the hypothetical one is normally 10^{-3} to 10^{-5} and might average 10^{-4}, or only 1/2000 as large as the porosity of 0.2 might suggest. The expulsion term depends on how freely water may be driven through the confining beds by the increased head imposed on the aquifer by waste injection. If the aquifer wedges out in other directions as well as updip, the increase in the rate at which water leaves the aquifer will be small unless the head is increased greatly by injection. In this event, the outflow could be accelerated by drilling "bleeder" wells along the coast and pumping them at a rate equivalent to that of injection. The water presumably would be discharged into the ocean and presumably would not be in a volume large enough that the differences in salinity and temperature from those of ocean water would be objectionable.

If, instead of wedging out beneath the sea, the injection aquifer cropped out beneath the sea, the expulsion would take place more readily unless the marine "subcrop" were a great distance away.

In either event the moving "front" of the body of injected waste would have to be monitored, on the assumption that the waste would still have its objectionable qualities at the time it reached the bleeder wells or the ocean and that its escape from the aquifer would be impermissible.

Obviously, control of the movement of injected waste in this way would be practical only on the basis of detailed subsurface information obtained by drilling and testing wells and by other means.

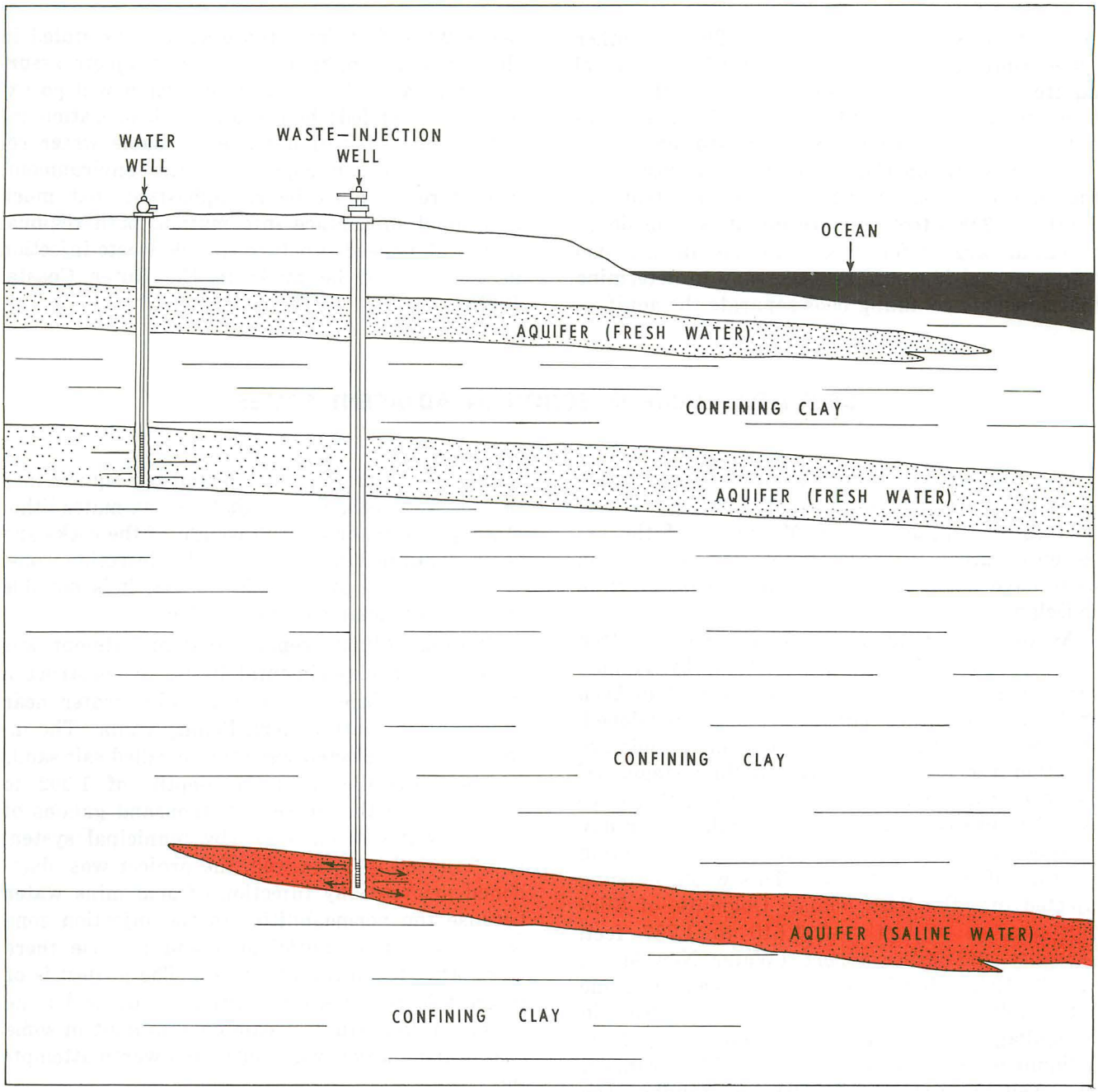

Figure 10. Schematic section showing waste-storage conditions in a coastal area.

Nace (1961, p. 7) discusses the use of Coastal Plain strata for waste storage and describes the possible ultimate fate of an injected fluid in this environment. He states: "Still another kind of storage environment is represented by parts of the Atlantic Coastal Plain, where Tertiary and Cretaceous salaquifers dip seaward beneath the continental shelf. Some geologists seem to assume that water in these aquifers invariably moves downdip, passing beneath the continental shelf to distant areas of discharge or leakage. If so, waste injected in the aquifers at places where the water is salty and unusable would move slowly downdip through the formation . . . on the other hand, we have already seen that the dip of the beds does not control ground-water movement. Moreover, theory indicates that in some coastal artesian aquifers salt water may move updip (H. H. Cooper, Jr., oral communication, 1960) motivated by imbalance between the potential gradient in the aquifer and the level of the sea. Any natural tendency toward updip motion could be accentuated by thermal convection. A crucial question for study is whether updip circulation can or does

occur offshore in deeper aquifers. This and other undetermined hydraulic characteristics of coastal aquifers require thorough study because they may turn out to be important, if not decisive, in evaluating these salaquifers for waste storage."

In summary, on the basis of the discussion in the preceding paragraphs, permeable strata at depths of 2,000 feet or more might be considered potential targets for waste storage. In any specific proposal it would be necessary to determine that adequate confining beds separate the aquifers below 2,000 feet from those above. As stated in the Introduction, there is never complete assurance that a waste-injection operation will go exactly as intended; hence, any such operation involves some risk of damage to usable water resources or other aspects of the environment. Therefore, it must be reemphasized that much additional subsurface information, both regional and local, is needed before specific waste-injection decisions could be made in the Outer Coastal Plain.

DEEP-WELL WASTE INJECTION IN ADJACENT STATES

It is pertinent to review some deep-well waste injection operations in adjacent States in view of the possible application in Maryland of the experience gained in those States. Waste-injection wells have not been reported in use in Virginia or Delaware.

As to Pennsylvania, G. H. Emrich (written communication, 1969) reports that, by August 1969, seven deep waste-injection wells had been drilled in that State. Three have been abandoned, and one is on standby. Two additional wells are in either the planning or the drilling stage. Of the seven completed wells, two in Erie, Pa., were used for injecting about 570,000 gallons per day of spent sulfite pulping liquor at an injection pressure of 900 to 1,000 psi. This waste is being injected into the Bass Islands Dolomite, of Silurian age, at a depth of 1,610 to 1,737 feet. Geraghty and Miller report (Water Newsletter, Jan. 22, 1969) that in late 1968 the casing of one of the wells blew 30 feet into the air, resulting in the spillage of several hundred thousand gallons of liquid wastes before the well could be capped. This well is presently (1969) on standby; the other is in use. Background information concerning this disposal operation is given in a report by Brown and Spalding (1966).

Warner (1967, p. 32) describes a well drilled in 1964 at Aliquippa, Pa., to dispose of steel-pickling liquor. Waste at this plant was originally injected at a rate of 100 gpm into strata in the Oriskany Group at a depth of 5,387 to 5,445 feet. This well was subsequently reconditioned (G. H. Emrich, written communication, 1969) and in August 1969 pickling liquor was being injected into an Upper Devonian shale sequence at a depth of 4,585 to 4,635 feet. The reported rate of injection is 125,000 gallons per day and the injection pressure about 5,000 psi. Such a pressure is equivalent to more than 1 pound per square inch per foot of depth, a value that approximates lithostatic pressure, or the full weight of the rocks and their contained fluids above the injection zone. If the reported pressure is correct, it is possible that hydrofracking is taking place.

Stefanko (1969) reports that an attempt was made, on an experimental basis, to construct a well for the injection of acid mine water near Marianna in southwestern Pennsylvania. The injection zones selected were the so-called salt sands in the Pottsville Group at depths of 1,302 to 1,565 feet. Although several thousand gallons of treated water from a nearby municipal system was injected into the well, the project was abandoned prior to any injection of acid mine water because the permeabilities in the injection zone were lower than anticipated and because there were other technical difficulties. The project is of interest in that deep-well injection of acid mine water, an important stream contaminant in some coal-bearing areas, was considered worth attempting.

Exclusive of brine-injection wells in oil fields, West Virginia had two disposal wells in operation in 1969. It is reported (Warner, 1967, p. 44; Wyrick, G. G., oral communication, 1969) that a well at Belle was completed in the "salt sand" of the Pottsville Group. The well is about 1,500 feet deep and is used to inject waste water containing 15 to 25 percent NaCl and $CaCl_2$ plus soluble organic compounds. The rate of injection is about 80 gpm at pressures up to 200 psi.

Another disposal well was drilled near Parkersburg, W. Va., to dispose of waste from manufacture of plastics (Warner, 1967, p. 45). This well was drilled to a depth of 1,682 feet and plugged back to 1,490 feet. The stratum used for

disposal is also a sand in the Pottsville Group. The waste contains 6 to 15 percent hydrochloric acid, 2 to 5 percent formic acid, small amounts of hydrofluoric acid, and up to 10,000 mg/l of organic compounds. The rate of injection is 100 gpm at a pressure of about 400 psi.

SUMMARY

This report by the U.S. Geological Survey has described the scientific and technical features of subsurface injection of waste liquids through deep wells and the uncertainties and related information requirements associated with the practice. While making clear the strictly factual and information role of the Federal Survey and the fact that it has no decision-making authority in this field, the report has suggested the principal policy aspects that must be considered by the agency or agencies having responsibility for approving, modifying, or denying applications for permits to inject liquid wastes through wells and in supervising the operation of permitted projects.

At the time of this report (1969) there were no waste-injection wells in Maryland, nor had applications for permits to install such wells been received by the State. As in other States having substantial concentrations of industry, however, interest in the possibilities of subsurface waste storage has been expressed in Maryland. Accordingly, the Maryland Geological Survey, as the State agency responsible for furnishing geologic and hydrologic information as background to State administration of natural-resource affairs, requested the preparation of this report as a part of the cooperative State-Federal program of resource evaluation.

The risks of damaging effects from carefully designed and operated waste-injection operations in Maryland range from high to low. (Of course, the risk of damage from a poorly designed or operated project is high no matter what the geologic and hydrologic framework may be.) This report divides Maryland into three major geologic and physiographic regions, which are, in turn, divided into eight subregions or areas, based on differences in geologic and hydrologic conditions. Geologic and hydrologic factors of importance in to deep-well waste injection are the presence or absence of a rock formation or zone having sufficient porosity or permeability to accept liquid wastes, and of layers of tight rock above and below that zone which are sufficiently thick, continuous, and extensive to confine the waste liquids to the storage aquifer.

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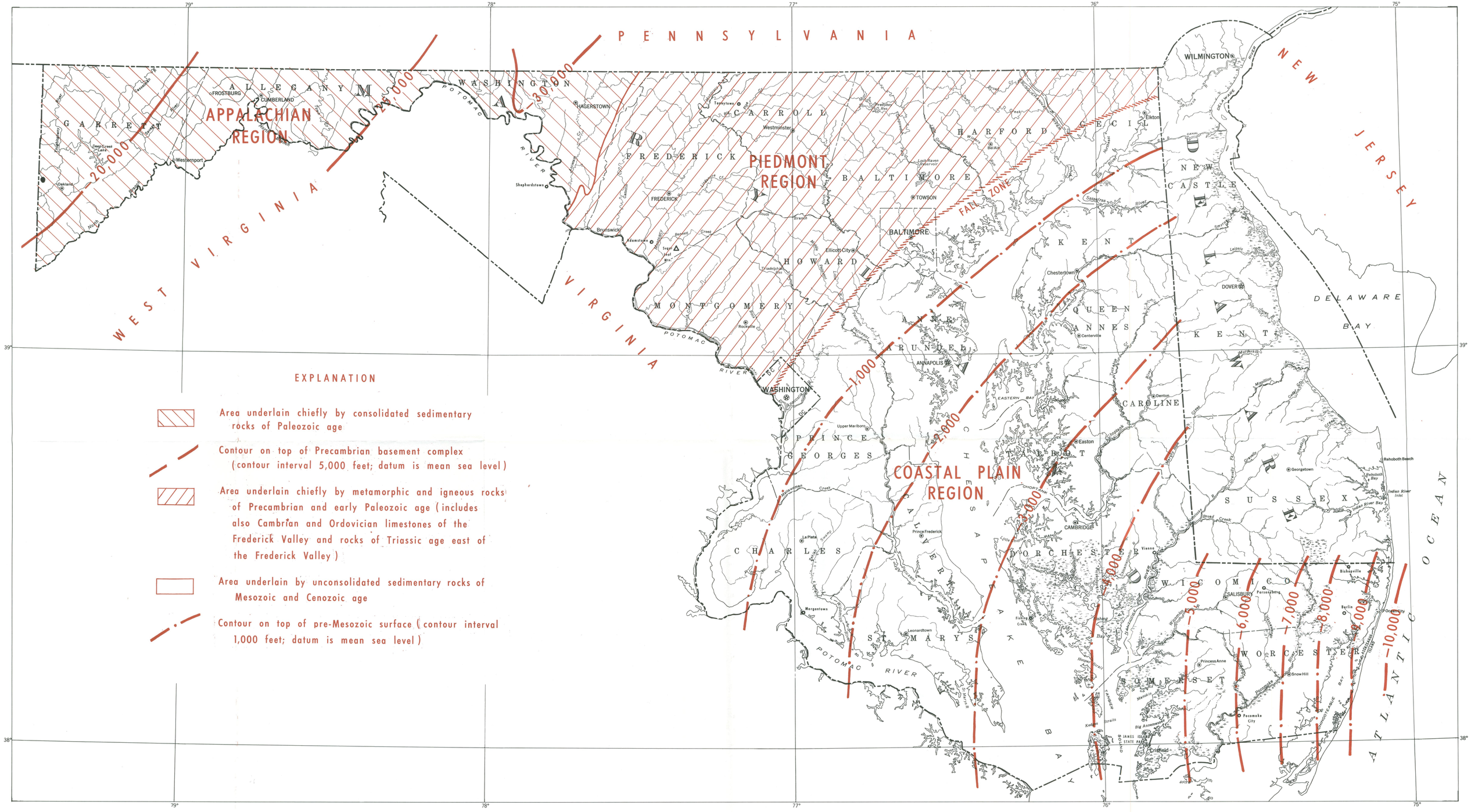
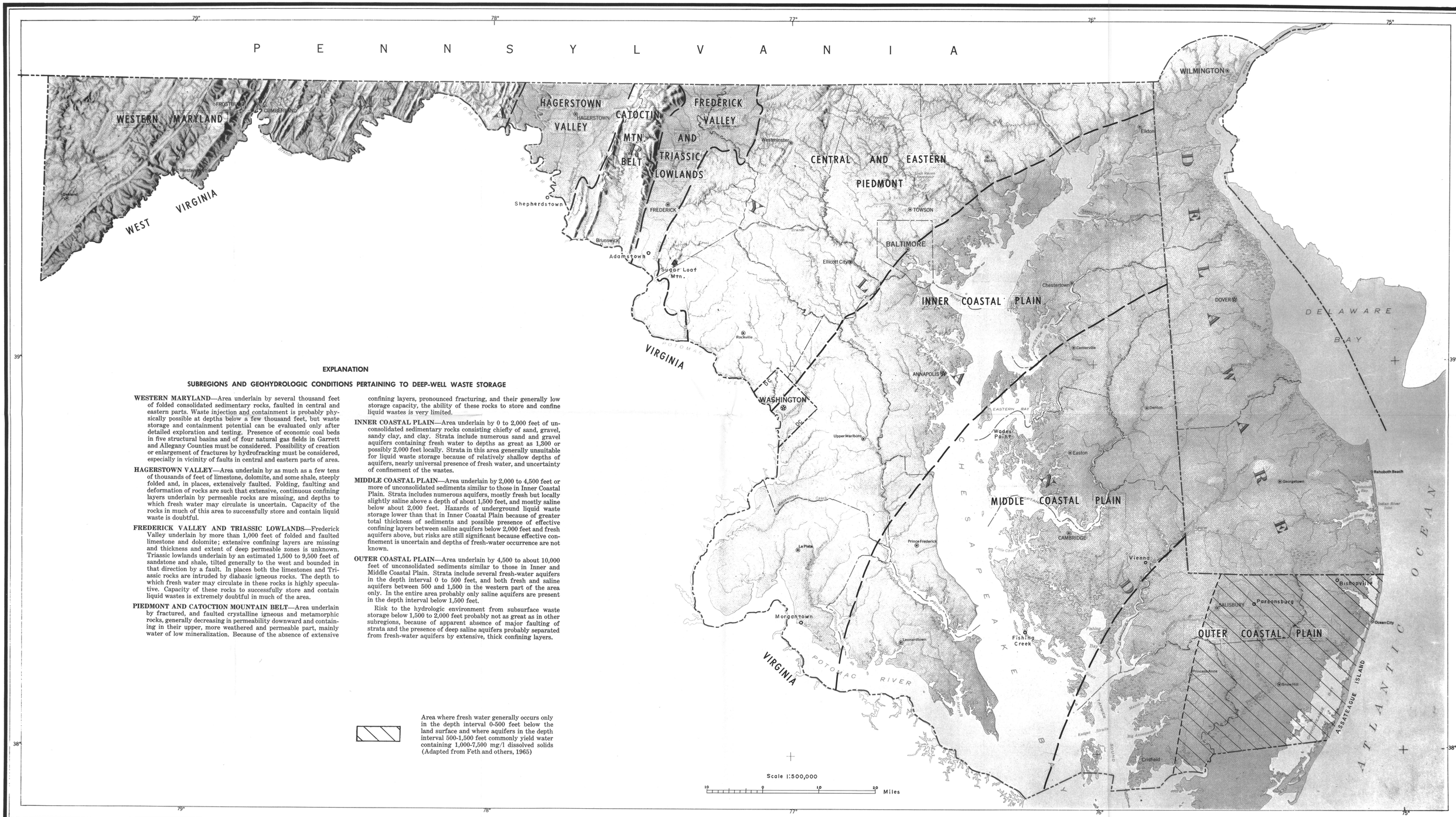


Figure 1. Map of Maryland showing major physiographic and geologic regions, location of places, and depth to basement rocks (Adapted from Bayley and Muehlberger, 1968).



EXPLANATION

SUBREGIONS AND GEOHYDROLOGIC CONDITIONS PERTAINING TO DEEP-WELL WASTE STORAGE

WESTERN MARYLAND—Area underlain by several thousand feet of folded consolidated sedimentary rocks, faulted in central and eastern parts. Waste injection and containment is probably physically possible at depths below a few thousand feet, but waste storage and containment potential can be evaluated only after detailed exploration and testing. Presence of economic coal beds in five structural basins and of four natural gas fields in Garrett and Allegany Counties must be considered. Possibility of creation or enlargement of fractures by hydrofracking must be considered, especially in vicinity of faults in central and eastern parts of area.

HAGERSTOWN VALLEY—Area underlain by as much as a few tens of thousands of feet of limestone, dolomite, and some shale, steeply folded and, in places, extensively faulted. Folding, faulting and deformation of rocks are such that extensive, continuous confining layers underlain by permeable rocks are missing, and depths to which fresh water may circulate is uncertain. Capacity of the rocks in much of this area to successfully store and contain liquid waste is doubtful.

FREDERICK VALLEY AND TRIASSIC LOWLANDS—Frederick Valley underlain by more than 1,000 feet of folded and faulted limestone and dolomite; extensive confining layers are missing and thickness and extent of deep permeable zones is unknown. Triassic lowlands underlain by an estimated 1,500 to 9,500 feet of sandstone and shale, tilted generally to the west and bounded in that direction by a fault. In places both the limestones and Triassic rocks are intruded by diabasic igneous rocks. The depth to which fresh water may circulate in these rocks is highly speculative. Capacity of these rocks to successfully store and contain liquid wastes is extremely doubtful in much of the area.

PIEDMONT AND CATOCTION MOUNTAIN BELT—Area underlain by fractured, and faulted crystalline igneous and metamorphic rocks, generally decreasing in permeability downward and containing in their upper, more weathered and permeable part, mainly water of low mineralization. Because of the absence of extensive confining layers, pronounced fracturing, and their generally low storage capacity, the ability of these rocks to store and confine liquid wastes is very limited.

INNER COASTAL PLAIN—Area underlain by 0 to 2,000 feet of unconsolidated sedimentary rocks consisting chiefly of sand, gravel, sandy clay, and clay. Strata include numerous sand and gravel aquifers containing fresh water to depths as great as 1,300 or possibly 2,000 feet locally. Strata in this area generally unsuitable for liquid waste storage because of relatively shallow depths of aquifers, nearly universal presence of fresh water, and uncertainty of confinement of the wastes.

MIDDLE COASTAL PLAIN—Area underlain by 2,000 to 4,500 feet or more of unconsolidated sediments similar to those in Inner Coastal Plain. Strata includes numerous aquifers, mostly fresh but locally slightly saline above a depth of about 1,500 feet, and mostly saline below about 2,000 feet. Hazards of underground liquid waste storage lower than that in Inner Coastal Plain because of greater total thickness of sediments and possible presence of effective confining layers between saline aquifers below 2,000 feet and fresh aquifers above, but risks are still significant because effective confinement is uncertain and depths of fresh-water occurrence are not known.

OUTER COASTAL PLAIN—Area underlain by 4,500 to about 10,000 feet of unconsolidated sediments similar to those in Inner and Middle Coastal Plain. Strata include several fresh-water aquifers in the depth interval 0 to 500 feet, and both fresh and saline aquifers between 500 and 1,500 in the western part of the area only. In the entire area probably only saline aquifers are present in the depth interval below 1,500 feet.

Risk to the hydrologic environment from subsurface waste storage below 1,500 to 2,000 feet probably not as great as in other subregions, because of apparent absence of major faulting of strata and the presence of deep saline aquifers probably separated from fresh-water aquifers by extensive, thick confining layers.

Area where fresh water generally occurs only in the depth interval 0-500 feet below the land surface and where aquifers in the depth interval 500-1,500 feet commonly yield water containing 1,000-7,500 mg/l dissolved solids (Adapted from Feth and others, 1965)

Figure 4. Subregions of Maryland with a brief description of the geologic and hydrologic factors pertaining to subsurface waste storage.

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