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Salt Deposits in the United States and Regional Geologic Characteristics Important for Storage of Radioactive Waste

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Preface

This report was originally prepared for Union Carbide Corporation, Oak Ridge National Laboratories, Oak Ridge, Tennessee, as part of the United States government effort to identify a site suitable for building a repository for disposal of high-level radioactive wastes. A 1957 report by the National Academy of Sciences–National Research Council recommended that such wastes be buried in a solidified form in subsurface deposits of rock salt (halite). Union Carbide Corp. contracted with the authors to conduct a national survey of salt deposits in the United States, and to describe important characteristics of each salt unit or province that are important for waste isolation and containment: thickness, depth, lateral continuity, homogeneity, and dissolution of salt beds, as well as the geologic structure, hydrology, and seismicity of the region.

The great deposits of rock salt in the United States include: Salina Group salts in the Michigan and Appalachian Basins, the Permian salts in the greater Permian Basin (including western Oklahoma), and the Louann Salt and salt domes of the Gulf Coast Basin. Other significant deposits are in the Paradox Basin and the Holbrook Basin (referred to as the "Supai Salt Basin" in this report). A number of smaller and/or thinner deposits were also characterized, so that the study covered all of the nation's salt deposits known at that time (in 1978).

The nation has two sites that have been highly regarded for disposal of radioactive wastes in salt deposits: the Waste Isolation Pilot Project (WIPP) in southeast New Mexico, and the Deaf Smith Site in the Texas Panhandle. The WIPP Site, near Carlsbad, has been receiving radioactive wastes left over from research and production of nuclear weapons since 1999, with disposal in the Salado Salt at a depth of about 2,100 feet. The Deaf Smith Site, southwest of Amarillo, was identified as a possible repository for radioactive waste from all but military-weapons facilities, with disposal in the San Andres Salt at a depth in excess of 2,000 feet. The WIPP Site is still operating, but studies of the Deaf Smith Site ceased in 1987 when the U.S. Congress amended the Nuclear Waste Policy Act in order to focus all future studies on the Yucca Mountain Site in Nevada.

Although this report is now dated, there is continued general interest in salt deposits throughout the United States for a variety of reasons. The original report had a very limited distribution, and an electronic copy has not been available. Thus, the Oklahoma Geological Survey is making it available online as an Open-File Report.

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Kenneth S. Johnson

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By

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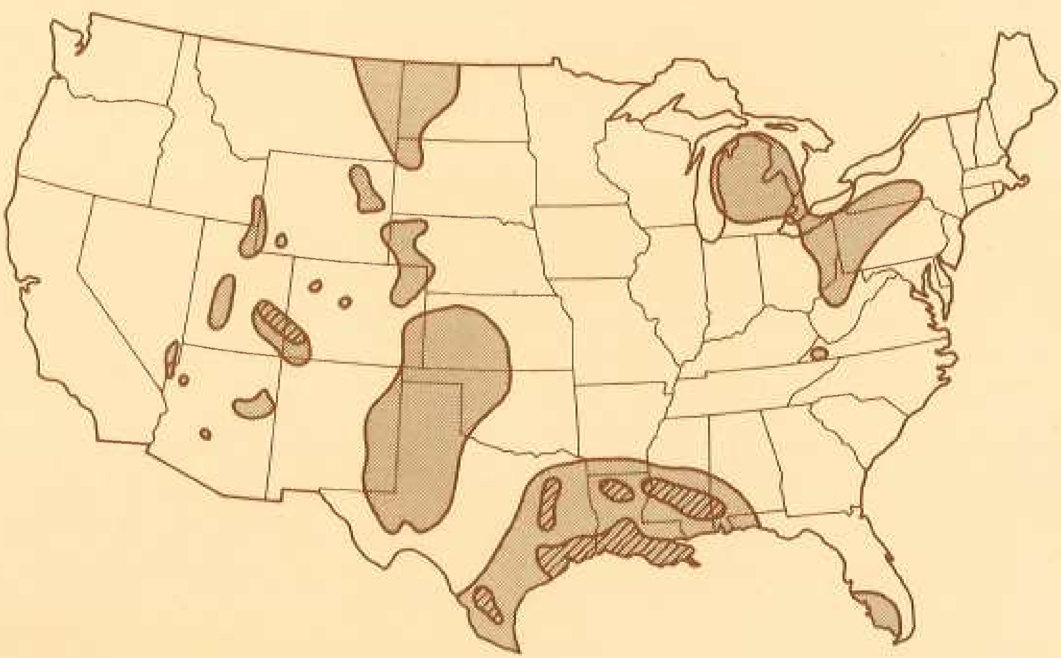

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CONTENTS

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Kenneth S. Johnson and **Serge Gonzales**

INTRODUCTION

Background

During the last three decades, the problem of safely managing high-level radioactive wastes, regardless of whether they have been generated from the manufacture of nuclear weapons or during the operation of nuclear electric-power plants, has grown in magnitude within the United States. This problem has become the focus of many studies by the federal government and private organizations as well as numerous publications, both in the scientific and popularized literature (for recent extensive bibliographies, see Schneider and Platt, 1974; Kubo and Rose, 1975; U.S. Energy Research and Development Administration, 1976a, 1976b). The proper management of these high-level wastes requires that they be stored or disposed of in such a way that their radionuclides will not appear in the biosphere in amounts that would constitute a biological hazard (International Atomic Energy Agency, 1977) and that these wastes must be isolated from the biosphere for long periods of geologic time.

The utilization of various geologic media for either the storage or disposal of high-level wastes has become the principal choice pursued in the United States. Several different geologic settings have been proposed and studied, such as the ocean sea bed in either submarine-trench or abyssal-plain areas, the Antarctic ice sheet, isolated alluvial valleys in the Western United States, and artificially formed nuclear chimneys in molten silicate rock, and many different rock types, such as clays and shales, granites, basalts, anhydrite, dry limestones (including chalks), and talc, but the primary focus in this country has been directed toward rock salt ever since a report by the National Academy of Sciences–National Research Council (1957) recommended that the wastes be buried in a solidified form within subsurface bedded salt deposits.

During the period 1963 to 1967, Oak Ridge National Laboratory conducted a series of research investigations to demonstrate the technical feasibility of this concept, using an abandoned salt mine beneath Lyons, Kansas, as a test site. This study, known as Project Salt Vault, concluded that disposal in bedded salt was feasible and that handling and emplacement equipment could be designed to safely transfer the solidified wastes sealed in canisters into a subsurface repository (Bradshaw and McClain, 1971). During this interval of time, several additional reviews by committees of the National Academy of Sciences–National Research Council continued to advocate the acceptability of bedded rock salt, and a report (National Academy of Sciences–National Research Council, 1970) summarized that group's support of salt as a repository medium. Recent studies of Permian salts in southeastern New Mexico by Sandia Laboratories are related to storage of wastes that result from military-weaponry production.

Investigations of rock salt have been expanded since the early 1970's to include both bedded and domal (diapiric) deposits (Martinez and others, 1975, 1976; Netherland, Sewell and Associates, 1976a). Other nations, such as Canada, the Federal Republic of Germany, and The Netherlands, which possess subsurface salt deposits, have also investigated this rock type extensively. In fact, the only currently operative subsurface repository, even though high-level wastes are not now being accepted for disposal, is located in the abandoned Asse salt mine in West Germany (Kühn and Hamstra, 1976).

Characteristics of salt deposits that are considered to be especially favorable for storage of high-level radioactive waste include the following:

(1) Many salt beds have remained undisturbed and without dissolution (dry) for tens to hundreds of millions of years, indicative of their long-term integrity and nondissolution by hydrologic systems;
(2) rock salt exhibits a high thermal conductivity, or the ability to dissipate large quantities of heat (as would be generated by high-level wastes);
(3) owing to its natural plasticity, salt is capable of "self-sealing" fractures developed in it, thus preventing access by fluids along zones of weakness, a problem that is typical of other, more brittle rocks;
(4) rock salt appears to undergo only minor radiolytic change owing to exposure to radioactivity;
(5) rock salt is comparable to concrete as a gamma-ray-shielding medium, and it has a compressive strength similar to that of concrete;
(6) salt deposits that are sufficiently deep and thick to be considered potential are widespread in this country and generally occur in areas characterized by low levels of seismicity and tectonic activity; thus, the potential for damage to repository structures (shaft, surface plant) resulting from earthquakes is greatly reduced;
(7) domestic salt resources are great enough so that if sites in several deposits were selected as repositories, no adverse effect on the resource base would be realized; repository sites also could be selected far from existing mines so that the latter would constitute no problem; and,
(8) rock salt can be easily mined at relatively low cost, and the technology for the underground excavation of salt is well developed; underground rooms opened in salt have remained stable for long periods of time, provided that adequate pillar size was incorporated into the mine design.

Recent articles by Cohen (1977) and Angino (1977) have reaffirmed the belief among many scientists and others that geologic isolation using rock-salt formations still represents the most promising alternative for handling high-level radioactive wastes, although the latter author also enumerated other geologic possibilities for those waste-producing nations that lack salt deposits.

Regional Geologic Characteristics Important for Waste Storage

The sole technical criterion that must be met in the storage or disposal of radioactive waste is that the repository must contain the radionuclides. In other words, the waste must be isolated from the biosphere until such time that, through radioactive decay, the radionuclides no longer pose a hazard to man and his ecosystem. The natural mechanism by which radioactive material could most likely be moved from a repository in an underground rock formation into the biosphere is by the action of ground water, and thus special attention must always be given to the geologic and hydrologic characteristics of a region being considered for storage of radioactive waste (International Atomic Energy Agency, 1977).

Rock-salt deposits have existed below the Earth's surface for many millions of years; many of them have not undergone significant changes for major periods of geologic time, and substantial parts of these deposits have remained free of circulating ground water. By study of the salt deposits, hydrology, geologic structure, and general geologic framework of a particular salt basin, it is possible to interpret the geologic processes that affected the region in the past and at present and also to forecast, in general, the future impact of such processes on a repository site for long periods of geologic time.

Because of the complexity of geological phenomena, each repository site must be selected on its own merits and considered unique. General characteristics of the geologic environment that govern the overall suitability of a salt deposit for waste storage were discussed in a recent report by the International Atomic Energy Agency (1977). The importance of these characteristics is discussed in the following paragraphs, and the specific characteristics for each of the salt basins in the United States are discussed in subsequent sections of this report.

Structure and Geologic Framework

The regional geology and geologic history of a salt basin must be known in order to understand the processes that have acted on a potential repository site in the past and that will affect containment of waste in the future. Regions that have been tectonically stable over the past tens of millions to hundreds of millions of years are likely to remain stable during the next several hundred thousand years. Areas of anticipated rapid uplift or strong deformation are less desirable for waste storage, because radionuclides in such a setting might escape as a result of such uplift and accompanying denudation or through disruption and distortion of the host rock. Some of the more important structural elements that should be studied for each deposit include:

Dip or inclination of strata. In bedded salt deposits, the preferred dip of strata is generally less than a few degrees, as this would enable design of nearly horizontal underground workings in the same rock layers over fairly large areas. Steep dips or tight folds with frequent reversals in dip also indicate that the rocks were subjected to deformation or tectonic stresses that may still be operating and that may have produced complex geologic structures.

Faults and joints. Faults and joints generally are not desirable in rocks that may be used for containment of waste. The self-healing plastic behavior of salt would most probably cause closing of the fractures in the repository bed itself, but the fractures in adjacent, more brittle rocks might constitute important pathways for circulating ground water. Faults and joints may also cause physical discontinuities in the salt that could adversely affect mining operations. A region with few faults or joints also might be suitable for waste storage if these structural features can be located and then avoided or circumvented in the excavations for waste emplacement.

Nature and extent of adjacent strata. Primary reliance for geologic containment of radioactive waste in salt rests on the properties of the salt itself, but additional protection may be gained by impervious strata located above and below the host rock. Thick beds of shale or other plastic-behaving rocks with low permeability would help protect the salt from circulating ground water and would tend to deform without fracturing, if there were subsequent disturbance of the repository area. The least desirable adjacent strata would be those containing large quantities of circulating water that is unsaturated with respect to salt.

Salt Deposits

The geometry, character, thickness, depth, and stability of the host rock for a radioactive-waste repository is critical to long-term containment of radionuclides. Bedded salt deposits attest their stability by having persisted tens of millions to hundreds of millions of years at the same location and, for the most part, in the same form as when they were originally deposited. The very existence of these salt deposits indicates that they have not been disturbed appreciably by circulating ground water. In some areas salt has flowed plastically in the geologic past to form diapiric structures consisting of enormous massive salt bodies; some of these salt domes and salt anticlines, however, have been stable for long periods of geologic time.

Depth of storage zone. A repository should be deep enough below the present land surface to ensure that its contained waste will not be exposed to the biosphere through erosion or denudation during its hazardous period. To negate the slow removal of the land surface through erosion, which generally is proceeding at an average rate of 2.5 to 7.5 m per 100,000 years in the continental United States (Ritter, 1967), and to avoid the shallow circulation of fresh ground water that might dissolve salt that contains a repository, the waste should probably be stored at least 300 m beneath the surface. The rate of plastic flow of rock salt resulting from overburden pressure increases markedly with depth, and therefore it is prudent to restrict mechanical mining operations in salt to depths no more than 1,500 m, and preferably less than 900 to 1,000 m. Thus, the optimum depth for a repository in salt ranges from 300 to 900 or 1,000 m. In this report, salts in that depth range are commonly referred to as being at ''moderate'' depth; those at lesser depths are commonly referred to as ''shallow,'' and those at greater depths are ''deep.''

Thickness and extent. In general, a salt unit must be of such a vertical and lateral extent that any fractures emanating from the repository will be sealed so as not to jeopardize containment. The host rock must also be extensive enough to provide for adequate heat dissipation. A thickness of at least 60 m of salt-bearing strata is preferred, although a lesser thickness of massive rock salt may be suitable and the salt-bearing unit should contain a minable salt bed about 6 m thick or more.

Homogeneity. In general, a high degree of homogeneity or consistency is desirable in salt deposits being considered for emplacement of radioactive wastes. Layers or irregular masses of some nonsalt rocks can adversely affect mining operations when they are encountered during repository excavation. Heat dissipation also may be adversely affected if large quantities of certain impurities occur near the disposal zone.

Salt dissolution. Rock salt is a highly soluble rock, and thus circulating ground water represents one of the major threats to containment of radioactive waste in salt beds or salt domes. For dissolution to occur, four requirements must be met (Johnson and others, 1977): (1) a supply of water unsaturated with respect to NaCl, (2) a deposit of salt through which or against which the water flows, (3) an outlet that will accept the resultant brine, and (4) energy (such as a hydrostatic head) to cause flow of water through the system. Rock salt at relatively shallow depth may be in contact with circulating ground water along its upper surface and/or its margins and to a lesser extent along its base; thus disposal zones should be deep enough and far enough away from such areas that the projected salt-dissolution rates, which incorporate projections of possible hydrologic and climatic changes, will not expose the waste during its hazardous period. The natural protection of salt from circulating ground water for long spans of geologic time is attested by the fact that salt beds of Permian and older age have remained intact and undissolved beneath overlying sediments in thousands of square kilometers in most parts of such major basins as the Michigan, Appalachian, Permian, and Paradox. These salts, and those of other basins as well, have survived for more than 200 million years, a time span well beyond that of the hazardous period during which radionuclides must be isolated from the biosphere.

Diapirism. In some basins, thick layers of salt buried at great depth have been deformed plastically owing to high pressures, and the salt has flowed slowly to form diapiric structures such as domes and anticlines. These types of structures may be especially suitable for waste disposal, provided that it can be determined that they are now stable and that flowage will not be renewed during the hazardous life time of the wastes. It should be noted that energy given off by the heat-generating wastes affects too small a volume of the salt mass and lasts for too short a time to initiate or reactivate diapirism.

Seismic Activity

Areas of low seismicity are favored for waste storage facilities. Violent earthquakes could damage surface facilities and entrances to the respository and could lead to temporary disruption of operation. The major seismic risk to long-term containment would be an earthquake-induced fault that might extend through the disposal zone in the future. Although the plastic behavior of salt would be likely to cause healing of fractures, ground water might circulate more freely along such a fault in adjacent rocks and thus tend to concentrate future salt dissolution along this zone of weakness.

Hydrology

Special attention must be paid to the hydrology of a prospective waste-storage area because of the extreme importance of keeping circulating water away from a repository located in rock salt. A comprehensive geohydrologic study of the entire region or basin should establish spatial relationships, interconnections, and fluid characteristics of all aquifers above and below salt beds (or above and alongside salt domes); identify recharge and discharge sites; and determine if salt has been or is being dissolved as well as the potential for future salt dissolution.

Surface water. The mere presence of surface streams, lakes, and ponds above an otherwise suitable repository site should not necessarily rule out its use. But it must be determined that this water would not interfere with the short-term operation of a disposal facility or compromise the long-term containment of any emplaced wastes. Salt deposits lying beneath flood plains or other areas prone to flooding may be especially difficult to develop, because extreme conditions could lead to the flow of water into underground excavations through open shafts or boreholes unless special design features are implemented. Surface streams may undergo marked changes in their flow regimes over long periods of time, and thus such future behavior as the rate of incision and shifting of the streambed must be predicted to ensure isolation of the waste for the required period of time.

Ground water. The repository must be free of circulating ground water, which represents the main threat to containment of radioactive waste placed in rock salt. Thus, the nature and characteristics of water-bearing strata near a potential disposal zone are critical elements in establishing its suitability. Investigations need to ascertain the nature and occurrence of ground-water flow and also the direction, velocity, and volume of the flow. In many areas, ground water is an important resource for municipalities, industry, and agriculture, and special care must be taken to protect these water resources.

Mineral Resources

Important nonsalt mineral resources, such as petroleum, potash, and sulfur, may be present near a salt deposit being considered as a waste repository. These minerals can occur in formations that overlie or underlie the salt unit, or in some cases they are interbedded with the salt, and it is necessary to weigh the need for a particular waste-repository site against the present or potential need for extracting mineral resources at that site. In general, a region would be viewed more favorably as a repository site if it had little or no potential for the discovery of scarce or valuable mineral resources. Owing to the great abundance and widespread distribution of domestic salt resources, there should be no adverse impact on the future supply of this commodity, even if radioactive waste is emplaced in salt at several sites. Another aspect of mineral investigations is the need to identify all preexisting boreholes, mine shafts, solution cavities, and other man-made excavations in the vicinity of a proposed repository. All such artificial openings that penetrate the salt zone represent potential migration paths for ground water, and it is essential that they all be plugged and sealed effectively.

Acknowledgments

We acknowledge and appreciate the continuing cooperation and support provided by staff members of the Office of Waste Isolation, Union Carbide Corp., Nuclear Division, and especially the efforts of Thomas F. Lomenick, who worked closely with us in preparing and reviewing this report. Thanks also are extended to David Deering and James Ingram for drafting the illustrations, and to William Rose for editing and coordinating the printing of the report.

GENERAL GEOLOGY OF SALT IN UNITED STATES

Origin of Salt and Salt Tectonics

The classic theory for the origin of thick salt deposits is that they form on the floor of a standing body of evaporating sea water that has a restricted connection with the open sea. As water is evaporated, the remaining sea water becomes increasingly saturated with respect to the dissolved solids or salts it contains, and eventually a series of "evaporite" minerals is precipitated. As normal marine water is evaporated, it becomes saturated first with calcium and magnesium carbonates (limestone and dolomite), then with calcium sulfate (gypsum and/or anhydrite), followed by sodium chloride (halite or rock salt), and finally by a series of potassium and magnesium salts (sylvite, carnallite, and other potash minerals). However, with variation in the salinity of water through time, and/or introduction of mud or sand into the basin, the precipitation of any evaporite mineral can be interrupted, causing interbedding of various rock types.

In some salt basins the evaporite cycle is represented by a vertical sequence consisting typically of carbonate at the base, gypsum (and/or anhydrite) in the middle, and halite (perhaps followed by potash salts) at the top. In other basins the evaporite cycle is represented by facies changes that occur horizontally over large areas. Thick sequences of limestone grade laterally and successively into dolomite, gypsum, and, finally, salt. In this way, thick sequences of salt have been deposited in some areas after the marine waters have been depleted of their carbonates and sulfates elsewhere.

Restriction of the evaporating basin from the open sea by a bar or sill was first proposed in 1877 by Ochsenius and later accepted, with modifications, by Branson (1915), Adams (1944), and King (1947). The basin might have been a lagoon, an estuary, or a large inland body of water having partially restricted contact with a larger body of saline water. Continued replenishment of saline water to the basin through the restricted passage thus allowed the precipitation of a considerable thickness of an essentially monomineralic deposit such as salt. Subsequent studies have also used variations of the bar theory to explain the origin of thick evaporites (Dellwig, 1955; Briggs, 1958; Hite, 1968; Dellwig and Evans, 1969; Peterson and Hite, 1969; Schmalz, 1969; Raup, 1970).

Examples of modern-day restricted environments that embody many of the features of the classic evaporite lagoon include the Gulf of Kara Bogaz on the Caspian Sea (Dzens-Litovskiy and Vasil'yev, 1962), the Bocana de Virrila on the Peruvian Coast (Morris and Dickey, 1957), and the north part of Great Salt Lake, Utah, when it was largely cut off from the main part of the lake by a semipermeable railroad causeway built in 1959 (Madison, 1970; Whelan, 1972).

In addition to the shallow-water conditions postulated for many ancient salt deposits, a deep-water environment has been advanced to explain some thick accumulations of monomineralic deposits during seemingly short spans of geologic time (Dellwig, 1955; Borchert and Muir, 1964; Wardlaw and Schwerdtner, 1966; Schmalz, 1969). Such a deep basin, perhaps several hundred meters deep, or at least as deep as the thickness of salt accumulation, is considered to be separated from the open ocean by a sill or shelf. Evaporation at the surface produces a more concentrated, denser brine that sinks to the bottom of the basin, until eventually the bottom waters are saturated with sodium chloride. With continued evaporation, crystals of halite would form at the surface and then redissolve as they settle toward the basin floor, thus further increasing the concentration of all brines in the basin. Eventually the basin would be filled with saturated brines, and continued evaporation would produce a shower of halite crystals that accumulate on the basin floor. Evaporite deposition might continue in this manner until the basin is filled or until the sill separating the basin from the open ocean is breached. Schmalz (1969) felt that the deep-basin model could be applied to the Salina Group salts in the Michigan basin, the Castile salt in the Delaware basin, and the Louann salt of the Gulf Coast region.

A relatively recent concept for deposition of evaporites is formation by precipitation from evaporating pore water present in unlithified supratidal mud flats or salt flats (called "sabkhas") in arid regions (Kinsman, 1966; Butler, 1970). Studies of modern sediments in the supratidal environment along the Trucial Coast in the Persian Gulf, along the shores of Baja California, and near lagoons along the Gulf Coast show that crystals and nodules of gypsum and/or anhydrite are now forming by displacement of soft sediments in the sabkhas. Although interpretation of such an environment is consistent with the findings in a number of evaporite units, especially gypsum and/or anhydrite units or other evaporites formed along the basin edges, most workers believe that variations of the bar-lagoon and deep-basin theories best explain the thick deposits of rock salt discussed in this report.

The thick layers of rock salt are now preserved in an undisturbed condition in many sedimentary basins where the salt is buried beneath younger sediments. In other basins, however, the salt has been deformed and has flowed to form a series of salt domes, salt anticlines, salt ridges, and salt pillows. These salt structures are commonly diapiric; that is, the plastic core of salt has pierced the overlying or surrounding rocks. Upward movement of salt is possible because the salt is less dense than surrounding compacted sediments, and once the upward movement is initiated it is possible for the top of the lighter salt mass to be injected into and through the overlying sediments. Not all salt structures are diapiric. In some areas the salt has flowed laterally within the evaporite bed and has bowed or arched the overlying strata upward without accompanying piercement.

The growth of salt structures is due to deep burial and the forces of buoyancy, but the initial cause of salt mobilization is uncertain in many cases and no unifying theory for the origin of all salt structures is recognized (Martinez, 1974). Salt flow was triggered in different areas by faulting, folding, submarine slumping, dissolution of salt in adjacent areas, differential loading, and still other causes (Kupfer, 1974).

Although most salt domes are roughly circular in plan view, and range in diameter from about 1 km to more than 6 km, there is great diversity in dome geometries, dome-to-cap-rock relationships, and dome-to-flank-rock orientations. The height of salt domes above their base is variable and depends in part on the thickness of the parent salt layer, the amount of this salt that is mobilized, and the thickness of overlying sediments that have been pierced. Heights of 3,000 to 6,000 m are not uncommon. Many domes flare outward at depth and may be connected at the base with the parent salt layer. Other domes are more constricted at depth and, like an inverted teardrop, may be pinched off at the base and disconnected from the parent layer.

Salt domes abound in the Gulf Coast basin, with more than 250 of them known or inferred in the 5 onshore subbasins, and this province is one of the major salt-dome areas of the World. Other significant salt-dome provinces include the North German basin, the Maritimes provinces of Canada, the Sverdrup basin of the Canadian Arctic Islands, and the Persian Gulf area of Iran. Aside from the Gulf Coast region, the only other generally accepted area of piercement domes in the United States is the Paradox basin of Utah and Colorado, where a major example is Upheaval Dome in Utah (Mattox, 1968). It has also been suggested that some of the Tertiary salts in Arizona may be domal in part, but available data do not seem to fully support this conclusion.

Salt anticlines are linear masses of rock salt over which younger sediments are arched and/or faulted owing to upward movement. Piercement anticlines formed by buoyant forces are abundant in the Paradox basin, and also are believed to be present at Sevier Valley; nonpiercement anticlines resulting from dissolution and/or tectonism are described from the Michigan and Appalachian basins. Salt-core anticlines are also known in the northwest part of the Northeast Texas basin and in southern Arkansas. Also, many of the interdomal structures, commonly called low-relief anticlines, in the Gulf Coast are supported at depth by salt that has flowed into anticlinal ridges.

Other examples of salt flowage in the United States appear to be related to regional deformation. Salt units deform plastically in response to folding and thrust faulting, and in some regions they are glide planes along which décollements have developed. As a result, salt units locally are highly contorted, folded, faulted, and/or brecciated. Deformation of salt has been described from the Virgin Valley (Nevada-Arizona), Sevier Valley (Utah), Eagle Valley (Colorado), Saltville (southwestern Virginia), and Idaho-Utah-Wyoming border salt deposits.

Distribution of Salt in United States

Rock-salt deposits are widely distributed within the United States and are known in 25 of the 50 states (fig. 1). Some of the deposits are extensive, such as the Salina Group salts of the Michigan and Appalachian basins, the Permian salts of the Permian basin, and the Louann salt and salt domes of the Gulf Coast basin. These occurrences rank among the greatest salt deposits of the world. Most salt deposits in the United States occur within major sedimentary basins (fig. 2) that received thick accumulations of sediment during periodic marine inundations of parts of the continent in the geologic past.

We have not included in the discussions here the various salt brines, salt springs, or recent surface deposits of salt but have limited our attention to deposits of rock salt—either bedded deposits or plastically deformed masses in salt domes and salt anticlines. A total of 19 such rock-salt deposits are therefore discussed in this report. The deposits are composed almost entirely of the mineral halite (NaCl), or common salt, although some are closely associated and interbedded with other evaporite or nonevaporite sedimentary rocks.

Salt deposits in the United States cover a wide span of geologic time and range in age from Silurian to Tertiary. Geologic conditions favoring deposition of thick layers of salt were repeated many times in various sedimentary basins. The oldest deposits are in the Northeast, in the Michigan and Appalachian basins, where Silurian-age bedded salts were deposited about 400 million years ago. The youngest deposits are in the Southwest and West, where Tertiary salts were laid down some 10 to 60 million years ago in the Luke, Red Lake, Virgin Valley, Piceance, and Green River deposits. The most numerous and widespread salts are those of Pennsylvanian to Jurassic age; during this time span, which ranged from about 150 to 320 million years ago, salts were laid down in the Gulf Coast, Permian, Supai, Paradox, Sevier Valley, Eagle Valley, Northern Denver, Powder River, Williston, and Idaho-Utah-Wyoming deposits.

One of the leading references of recent years to United States salt deposits became available in 1962, when the U.S. Geological Survey released its *Summary of Rock Salt Deposits in the United States as Possible Storage Sites for Radioactive Waste Materials*

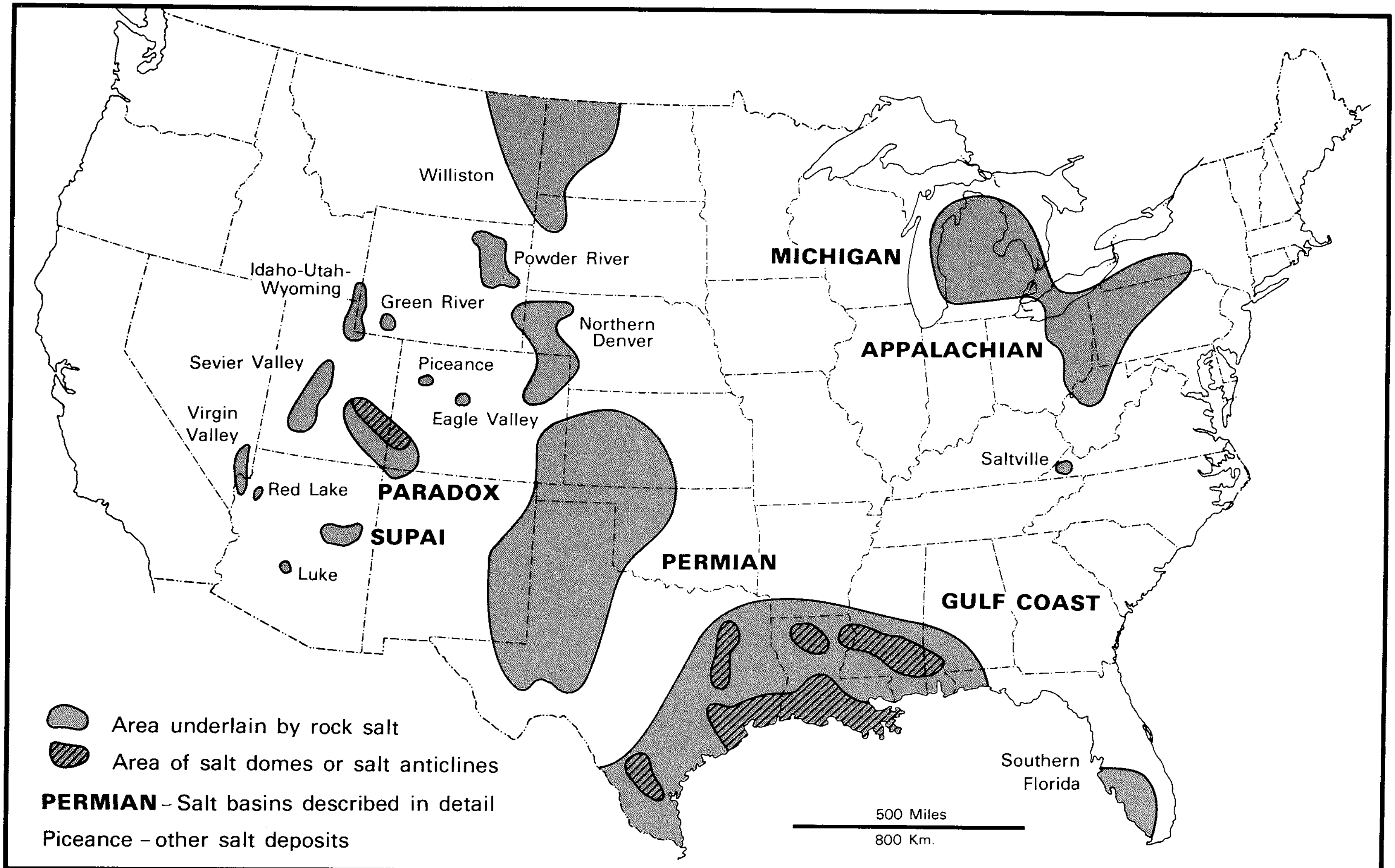


Figure 1. Map showing rock-salt deposits in United States.

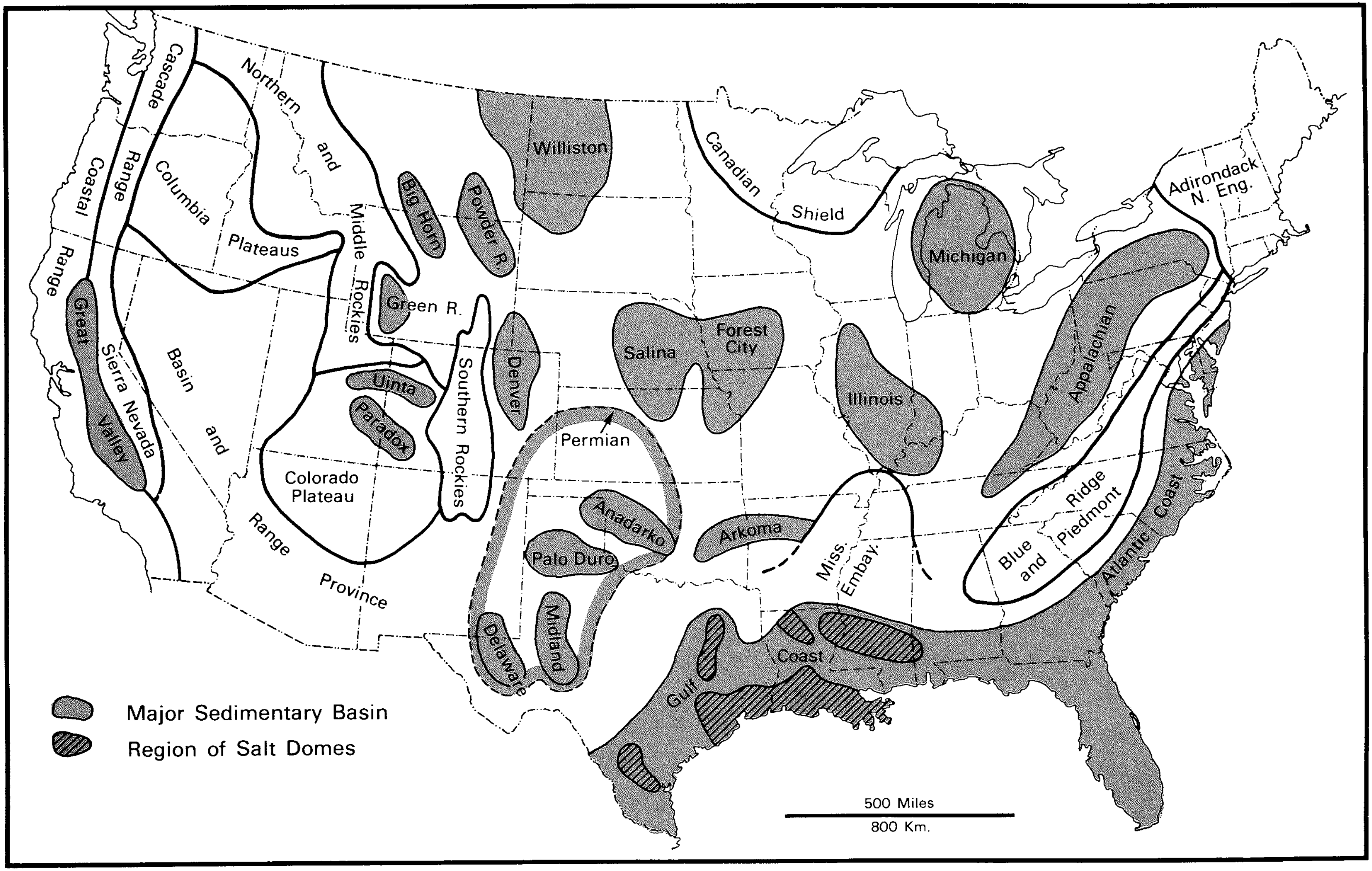


Figure 2. Map showing major sedimentary basins and other principal tectonic features of United States.

(Pierce and Rich, 1962). The report is an excellent compilation of data on the distribution and geology of salt deposits known at that time. Since then, several other major reports have synthesized information on salt deposits or have presented data on newly discovered salt deposits. The Northern Ohio Geological Society published the proceedings of its four *Symposia on Salt* in 1963, 1966, 1970, and 1974, and in 1968 The Geological Society of America released its Special Paper 88, a symposium on *Saline Deposits.* Halbouty (1967) published his classic report on salt domes in the Gulf Coast region, and in 1968 The American Association of Petroleum Geologists released Memoir 8 on *Diapirism and Diapirs.* Lefond (1969) compiled a comprehensive report entitled *Handbook of World Salt Resources.* In addition to these major reports, we have also relied heavily in preparation of this report upon the detailed studies of specific deposits published by The American Association of Petroleum Geologists, the U.S. Geological Survey, and the various State geological surveys and geological societies.

MICHIGAN BASIN

Structure and Geologic Framework

The Michigan basin is a major sedimentary and structural basin that embraces all of Michigan, as well as parts of Wisconsin, Illinois, Indiana, Ohio, and Ontario (fig. 3). It is bounded on the north and northeast by the Canadian shield, on the east and southeast by the Algonquin arch in Ontario and the Findlay arch in northern Ohio, on the southwest by the Kankakee arch in northern Indiana and northeastern Illinois, and on the west and northwest by the Wisconsin arch and Wisconsin dome (Ells, 1967, 1969). Much of the data presented here on the Michigan basin is summarized from an earlier report by Johnson and Gonzales (1976).

The basin lies in the tectonically stable interior of North America and is characterized by essentially flat-lying sedimentary rocks that are folded or faulted at only a few places. Strata dip gently into the center of the basin from the adjacent arches and shield area at a rate of 5 to 10 m per km (¼ ° to ½ °).

The deepest part of the basin apparently underlies Clare and Gladwin Counties, in the central part of Michigan's Southern Peninsula, where about 5,000 m of sedimentary rocks are believed to overlie the Precambrian (Ells, 1967). These sedimentary rocks include strata of Cambrian, Ordovician, Silurian, Devonian, Mississippian, Pennsylvanian, and Jurassic age. They are chiefly carbonates, shales, evaporites (salt and anhydrite), and sandstones (fig. 4). They are overlain at most places by Pleistocene glacial drift that averages between 60 and 90 m in thickness but that is more than 275 m thick locally.

The basin may have first developed as an embayment as early as Cambrian time (Fisher, 1969). Throughout the remainder of the Paleozoic Era, the basin continued to subside more than the adjacent regions, and thus it received a great thickness of sediments in its central part. The major period of subsidence took place in Late Silurian time, and this accounts in part for the deposition of the thick Salina salts in the Michigan basin.

Of principal interest for this report are the sedimentary rocks and geologic history of the Silurian and Devonian Periods, for these strata include the thick deposits of rock salt in the Michigan basin. Carbonates (limestone and dolomite) that formed during Early Silurian time represent deposition in shallow and warm marine waters. This carbonate deposition reached optimum conditions later during the Middle Silurian, when the Niagaran reef platform developed along the borders of the Michigan basin (Briggs and Briggs, 1974). The reef bank ranges in width from 8 to 30 km and separates a back-reef lagoonal zone outside of the basin from a shelf area and the central-basin area enclosed by the reef. The shelf area, which is about 20 to 30 km wide in the north and 30 to 60 km wide in the south, was favorable for the growth of numerous pinnacle reefs, many of which are prolific oil and gas reservoirs.

The Salina evaporites (Late Silurian) were not deposited until after major development of the Niagaran reefs had ceased in the Michigan basin (Briggs and Briggs, 1974; Mantek, 1973). Marine regression led to restricted circulation of the waters in the Michigan basin compared to those of the open ocean, and, as a result, the waters in the basin were evaporated and bedded salts were deposited when the water became saturated with sodium chloride. Intermittent replenishment of marine water to the basin permitted deposition of thick sequences of rock salt that extended throughout most of the Southern Peninsula. During periods of marine transgression the basin was flooded, and carbonates and other normal-marine sediments were deposited. Salina deposition is

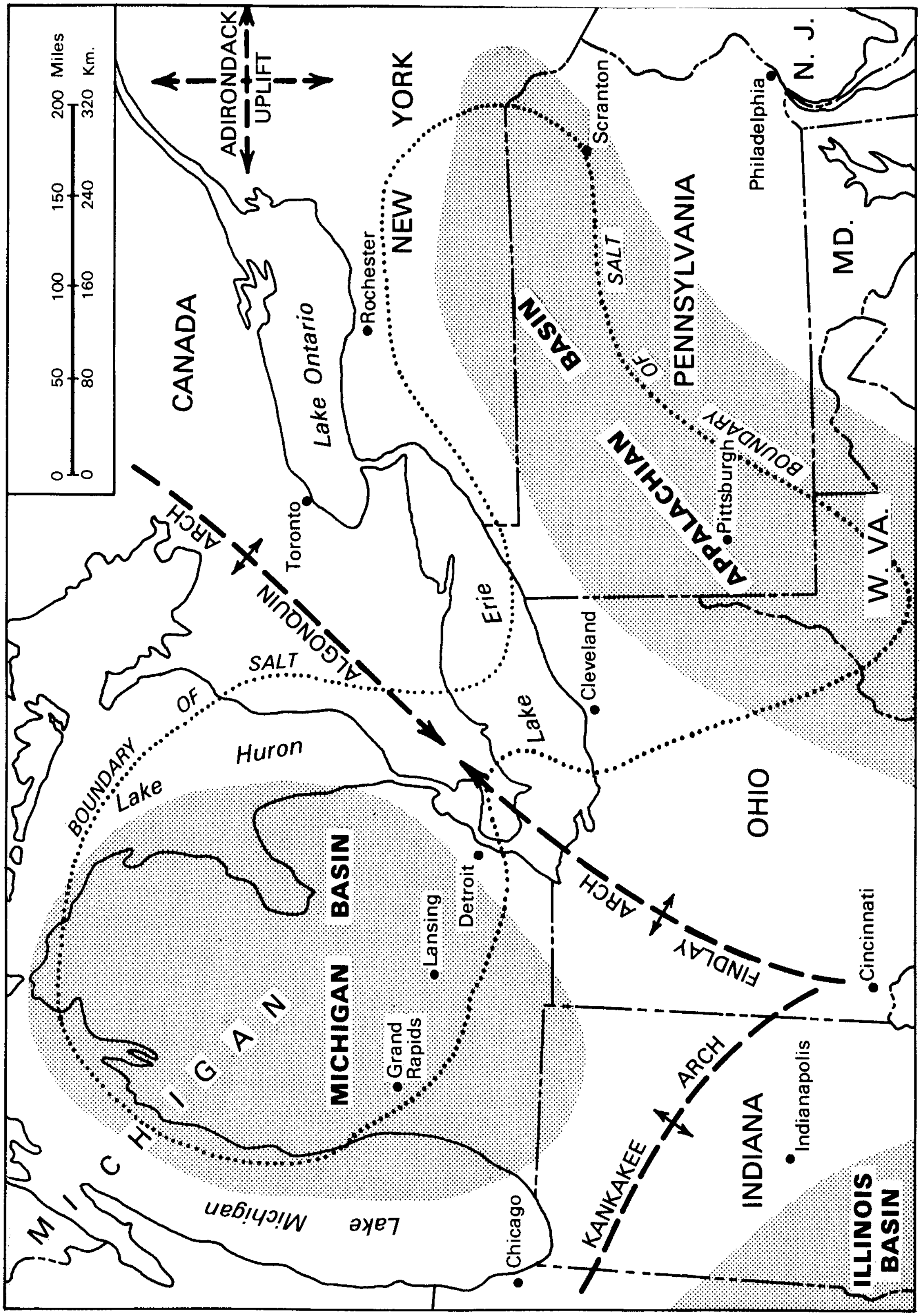


Figure 3. Map of Michigan basin and part of Appalachian basin showing areas underlain by Salina salts of Silurian age.

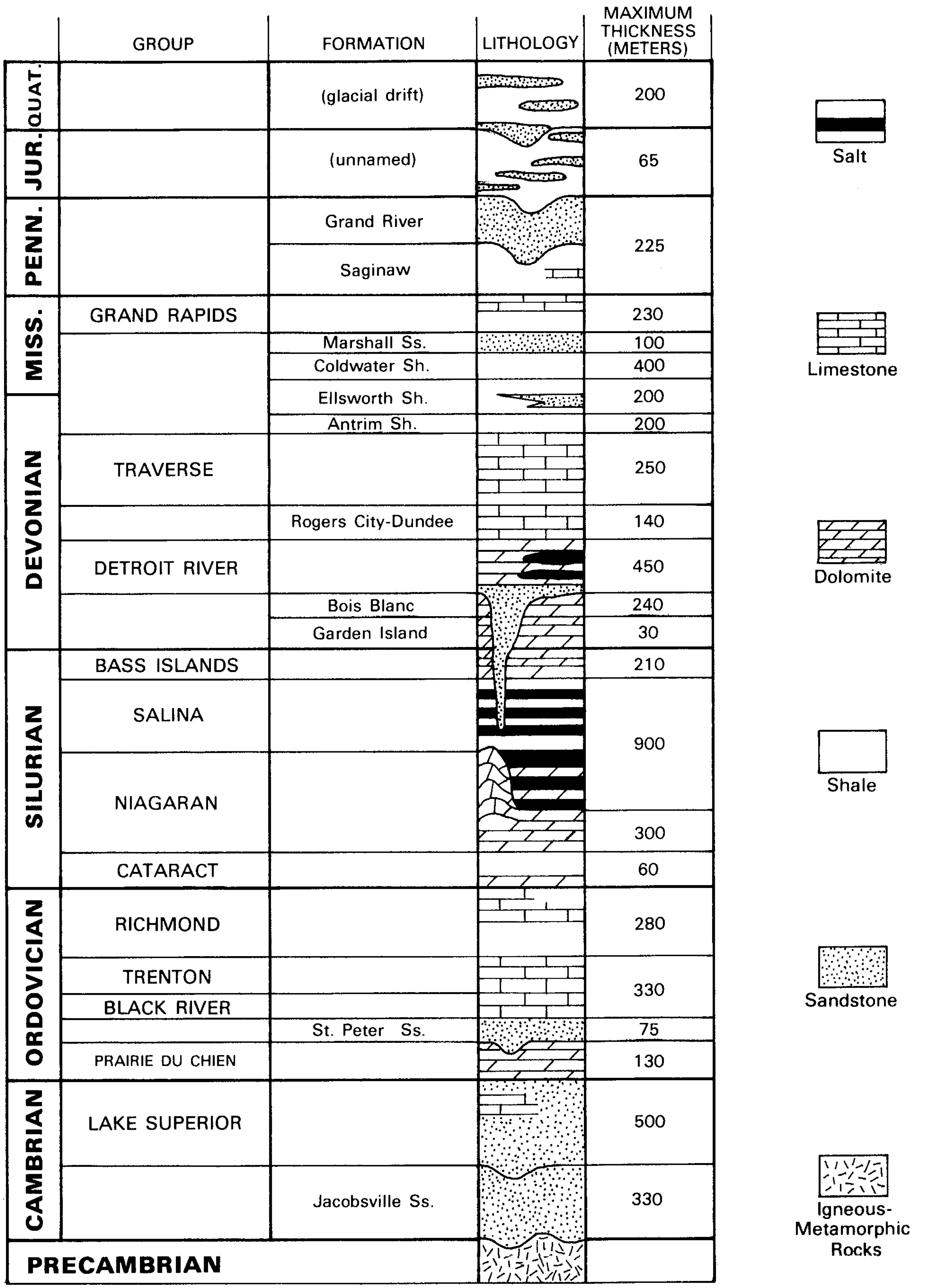


Figure 4. Stratigraphic succession in Michigan (modified from Michigan Geological Survey, 1964).

therefore characterized by a series of marine transgressions and regressions, with evaporites being formed during the regressions.

Following deposition of the Salina Group, the Bass Islands dolomite was laid down during a minor transgression that preceded the draining of marine waters from the Michigan basin and the subsequent erosional period that produced the Silurian-Devonian unconformity. Total thickness of Silurian strata ranges from 200 to 500 m in the south to 1,200 m in the central part of the basin (Fisher, 1969).

Early Devonian dolomites comprise transgressive-marine shelf carbonates deposited unconformably upon the low-relief surface of eroded Bass Islands strata (Gardner, 1974). During subsequent deposition of the Middle Devonian Detroit River Group, the northern part of the basin became more restricted until a series of salts and anhydrites was laid down with the carbonates. Landes (1951) felt that these salt beds were the result of leaching and redeposition of salt from the older Salina Group. The Mackinac Breccia is a term used to describe zones of fragmented, angular rock that encompass strata ranging in age from the Salina through the Detroit River. The breccia represents collapse structures that resulted from dissolution of the Salina salts in Middle Devonian time (Landes, 1959).

Following this, a series of limestones, designated the Dundee Limestone and the Traverse Group, were deposited, and this in turn was followed by deposition of the Late Devonian-Early Mississippian Antrim and Ellsworth Shales. The total thickness of Devonian strata ranges from about 100 m in the south to 1,000 m in the north-central part of the basin (Fisher, 1969).

Mississippian, Pennsylvanian, and Jurassic rocks consist chiefly of shales and sandstones, and they are restricted to the central part of the basin. Their aggregate thickness is about 1,000 m in this region.

Thick glaciers covered all of Michigan and surrounding areas during the Pleistocene Epoch. A series of four major ice sheets advanced southward across the region and then retreated, leaving behind thick deposits of glacial drift that mantle the bedrock. The thickness of the drift is more than 60 m in much of the state, but locally it exceeds 275 m in the north-central part of the Southern Peninsula (Akers, 1938). The drift is thin or absent locally, particularly in the northeast, northwest, south-central, and east-central parts of the basin (fig. 5).

The most significant structural feature affecting Paleozoic and younger rocks in the Michigan basin is the Howell anticline, a northwest-trending fold located in the southeast part of the basin. Ells (1969) regarded this fold as the largest of several northwest-plunging, subparallel structures on a broad, uplifted block designated the Washtenaw anticlinorium.

Northwest-trending anticlines with salt-filled cores are developed within Salina and younger rocks in the central part of the Michigan basin (Ells, 1967). These structures resulted from the draping of strata over elongated lenticular masses of Salina salt that remained after salt underlying adjacent areas was dissolved by circulating ground water.

Major faults within the Michigan basin appear to be minimal. Probably the most significant fault is one on the west flank of the Howell anticline, where a fault in the basement presumably grades upward into a sharp flexure in Ordovician and younger strata (Ells, 1969). Local anomalous changes in dips and outcrop patterns suggest the presence of faults with small displacement, although in many cases the relationships are far from conclusive in proving the existence of faults. Prouty (1976) also contended that certain surface lineaments detected on aerial photographs and satellite imagery might have been controlled by subsurface faults. More thorough regional and local studies are needed on

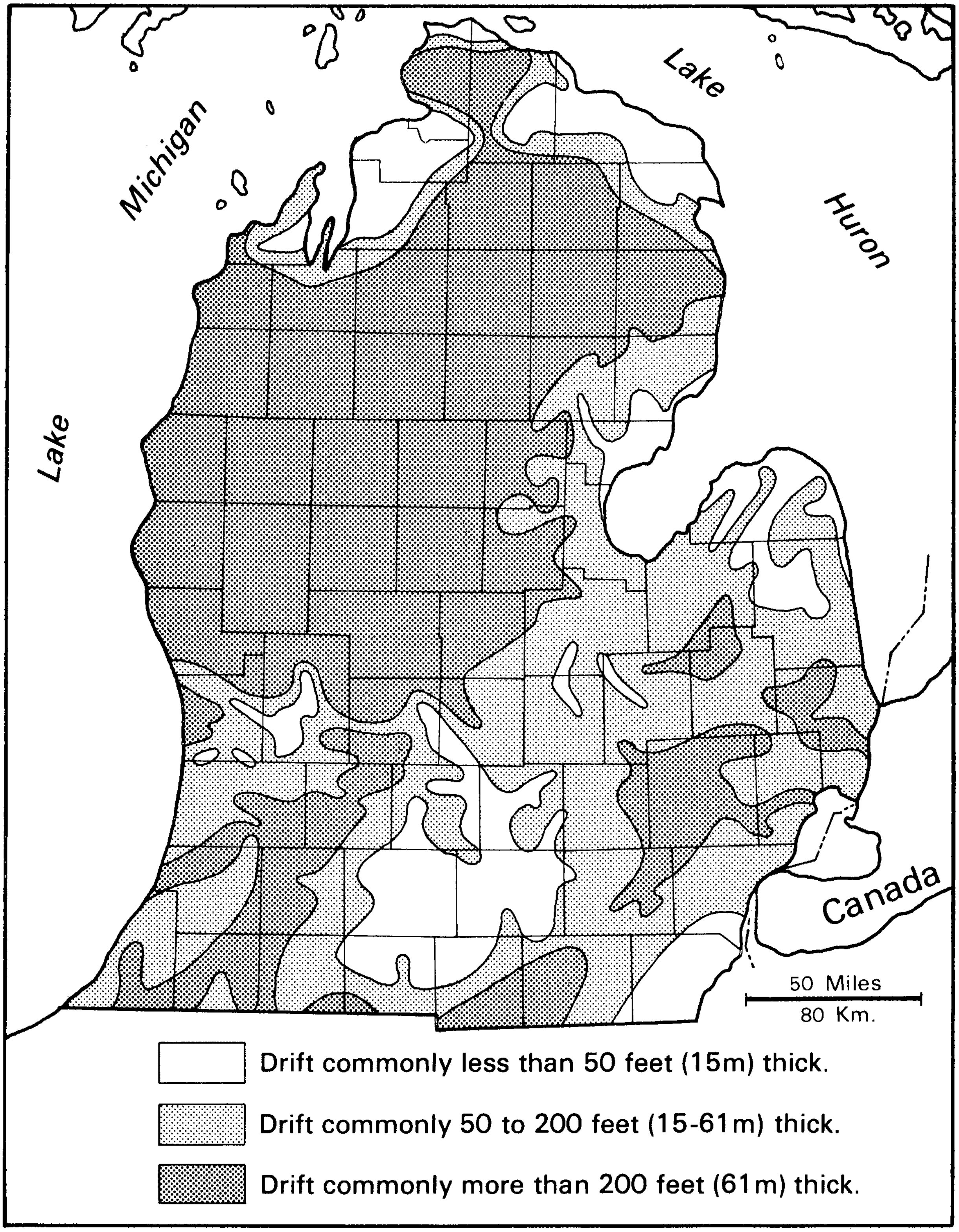


Figure 5. Map showing thickness of glacial drift in Michigan's Southern Peninsula (after Akers, 1938).

possible faulting in the Michigan basin before any particular area can be considered free of such structures.

Thus, the history of the Michigan basin has been one of tectonic stability since the beginning of the Paleozoic Era. The region has not been affected by mountain-building processes, and the Salina salts and younger strata appear virtually free of significant deformation except near the Howell anticline and various salt-core anticlines. Since the final retreat of Pleistocene glaciers, land areas within the Michigan basin, relieved of a great weight of ice, have undergone some measure of glacial (isostatic) rebound, but this does not pose a deformational hazard.

Rates of erosion in the Michigan basin can be estimated from general knowledge of the landscape and of the sediment loads in streams draining the area. Using data presented by the Great Lakes Basin Commission (1975), the rates of denudation and stream incision appear to be in the range of only 50 to 100 m over the next several hundred thousand years. The north half of the Southern Peninsula is furthermore being eroded at a much slower rate than the south half.

Soluble rocks, such as salt, gypsum, limestone, and dolomite, are being dissolved locally by surface waters and by ground waters. Sinkholes and other karst-like features are known in some parts of the Michigan basin where carbonate strata crop out. The dissolution of salt deposits is discussed later.

Salt Deposits

Silurian-age salt deposits of the northeastern United States make up one of the greatest accumulations of salt in the world (Pierce and Rich, 1962; Lefond, 1969). These thick, high-purity deposits occur in the Salina Group and underlie a total area of about 250,000 sq. km that embraces both the Michigan and Appalachian basins (fig. 6).

The Michigan basin contains the major portion of the Salina Group salt, which, for example, attains an aggregate thickness of more than 600 m in the central part of the basin. The thickness of individual salt beds and of the entire salt-bearing sequence decreases toward the edges of the basin. The depth to the top of the salt ranges from about 1,800 m in the center of the basin to between 150 and 300 m along the margins.

The northern half of the Michigan basin also contains salt in the Devonian Detroit River Group. This salt section is more than 150 m thick and contains as many as 8 different salt beds, the thickest of which is more than 30 m thick. Although the top of the salt is more than 1,200 m deep in the central part of the state, it is less than 400 m deep locally along the northeastern margin of the basin.

The Appalachian basin (described elsewhere) contains a southeastward extension of the Salina Group salt sequence. Here, the salt reaches an aggregate thickness of more than 60 m in parts of eastern Ohio and more than 150 m in south-central New York (fig. 6). Dipping southeastward into the Appalachian basin, the salt sequence lies from 300 m to more than 1,500 m below the surface in these states.

Salina Group

The Salina Group consists of a number of stratigraphic units that are equivalent to formations, with each unit composed predominantly of salt, carbonates, or shales. Individual units have a similar lithologic character over a wide geographic area, and the distinctive mechanical-log curves for each unit permit reliable correlations over large distances (Ells, 1967; Rickard, 1969).

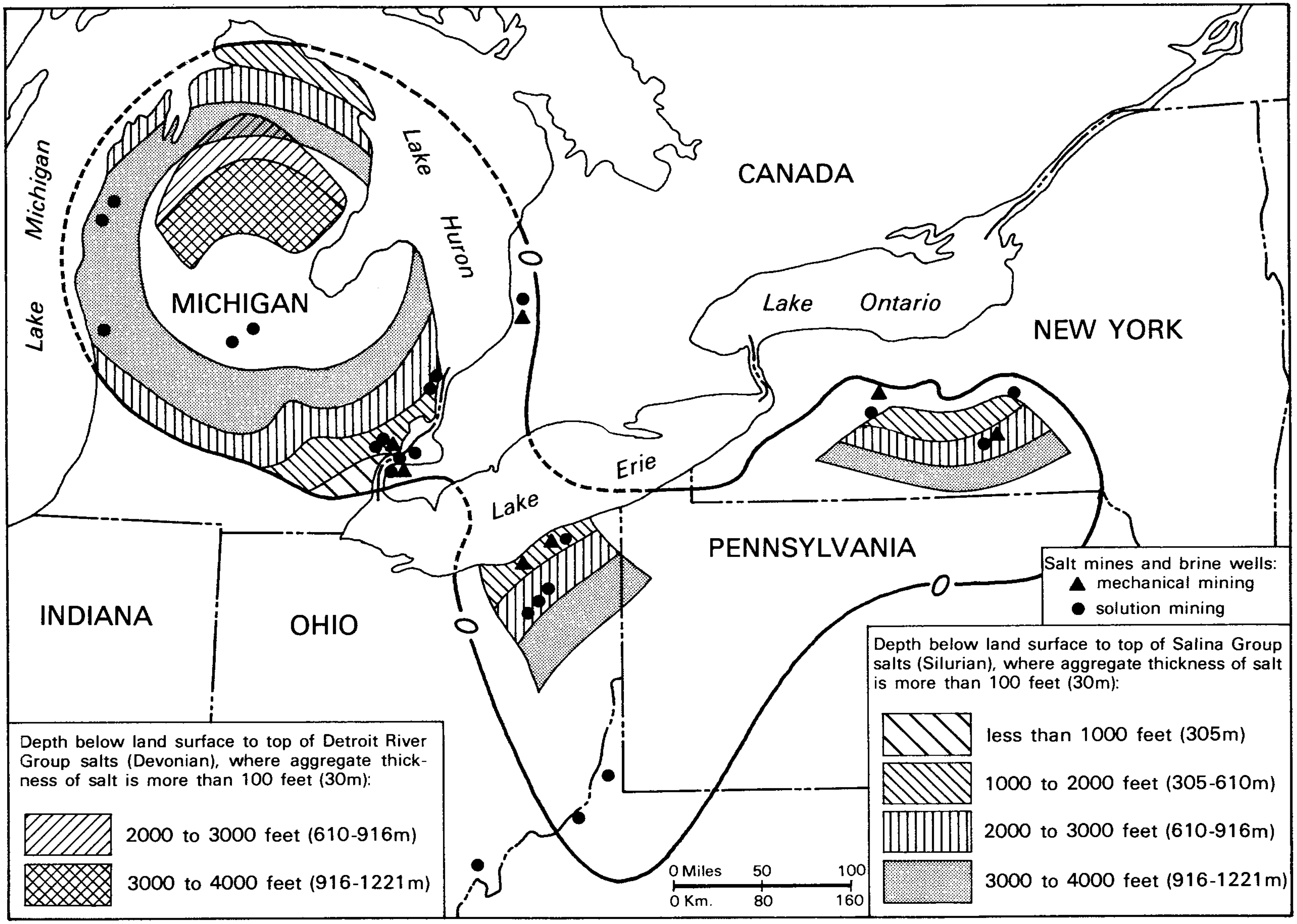


Figure 6. Map showing distribution and depth below land surface of Silurian and Devonian salt deposits in Michigan, Ohio, New York, and Pennsylvania.

In the center of the basin, Salina Group salts have an aggregate thickness of more than 600 m and exist at depths greater than 1,800 m below land surface (fig. 7). Both the aggregate thickness of salts and the depth below land surface to the top of the salts in the Salina decrease outward from the center of the basin (fig. 8). The depth to the top of the Salina salts, as shown on this map, and on each map for individual salt units, is approximate and is contoured from data interpreted from mechanical logs of 30 wells drilled throughout the basin.

An example of the lithology of the Salina Group, as interpreted from mechanical and sample logs, is presented in figure 9 for an oil-well test drilled near the edge of the basin where the various salts are moderately thick and are at fairly shallow depths. The current terminology and rock divisions of the Salina Group are based largely on the work of Landes (1945) and Evans (1950). Landes divided the Salina Group into units A through G, from oldest to youngest, and Evans further divided the A units. The following descriptions of individual units are largely from the reports by Ells (1967) and Mesolella and others (1974).

A-1 salt. The A-1 salt is the deepest unit of the Salina Group and rests conformably upon the limestones and dolomites of the underlying Niagaran Group. The A-1 contains clean salt in most parts of the basin interior, but it also contains a few thin layers of potash (Anderson and Egleson, 1970; Matthews, 1970) in deeper parts of the basin.

The thickness of the A-1 salt is more than 60 m in most parts of the basin interior, reaching some 150 m in the center (fig. 10). Toward the margins of the basin, the salt thins abruptly and grades laterally into anhydrite near the basinward edge of the Niagaran reef platform. The depth to the top of the A-1 salt is as much as 2,500 m in the central part of the basin, but in the northeast and southwest parts of the basin the salt is only a little more than 900 m below the surface.

A-2 salt. The A-2 salt is the thickest massive salt unit in most parts of the Michigan basin. Separation from the deeper A-1 salt is afforded by the A-1 carbonate (fig. 9). The A-2 contains clean salt in the interior of the basin but grades laterally into anhydrite along the margins of the basin.

The thickness of the A-2 salt is more than 100 m in most areas and exceeds 150 m in the deeper parts of the basin (fig. 11). Depositional limits of this salt are approximately the same as those for the A-1 salt. In the central part of the basin, the top of the A-2 salt is more than 2,000 m below the land surface; however, the depth to the top of this unit decreases to between 900 and 1,200 m along the southeast, southwest, and northeast edges of the basin.

B salt. The B salt, the next youngest salt unit, consists of clean salt in the lower part and salt with thin interbeds of shale and dolomite in the upper part. The underlying A-2 carbonate separates it from the deeper A-2 salt (fig. 9). As with the older salts, the B grades laterally into anhydrite toward the margins of the basin; but the salt extends farther to the north and southeast than the other salts (fig. 12).

The thickness of the B salt is more than 100 m in most parts of the basin interior and is more than 150 m in the center. The clean salt in the lower part commonly constitutes about one-half the total thickness of the B unit. The depth to the top of the B salt is just over 2,000 m in the central part of the basin but is only 600 to 900 m in the southeast, southwest, northeast, and northwest parts of the basin.

D salt. The D unit consists of two moderately thin salt beds separated by a thin medial dolomite bed (fig. 9). The total thickness of the unit ranges from 10 to 30 m.

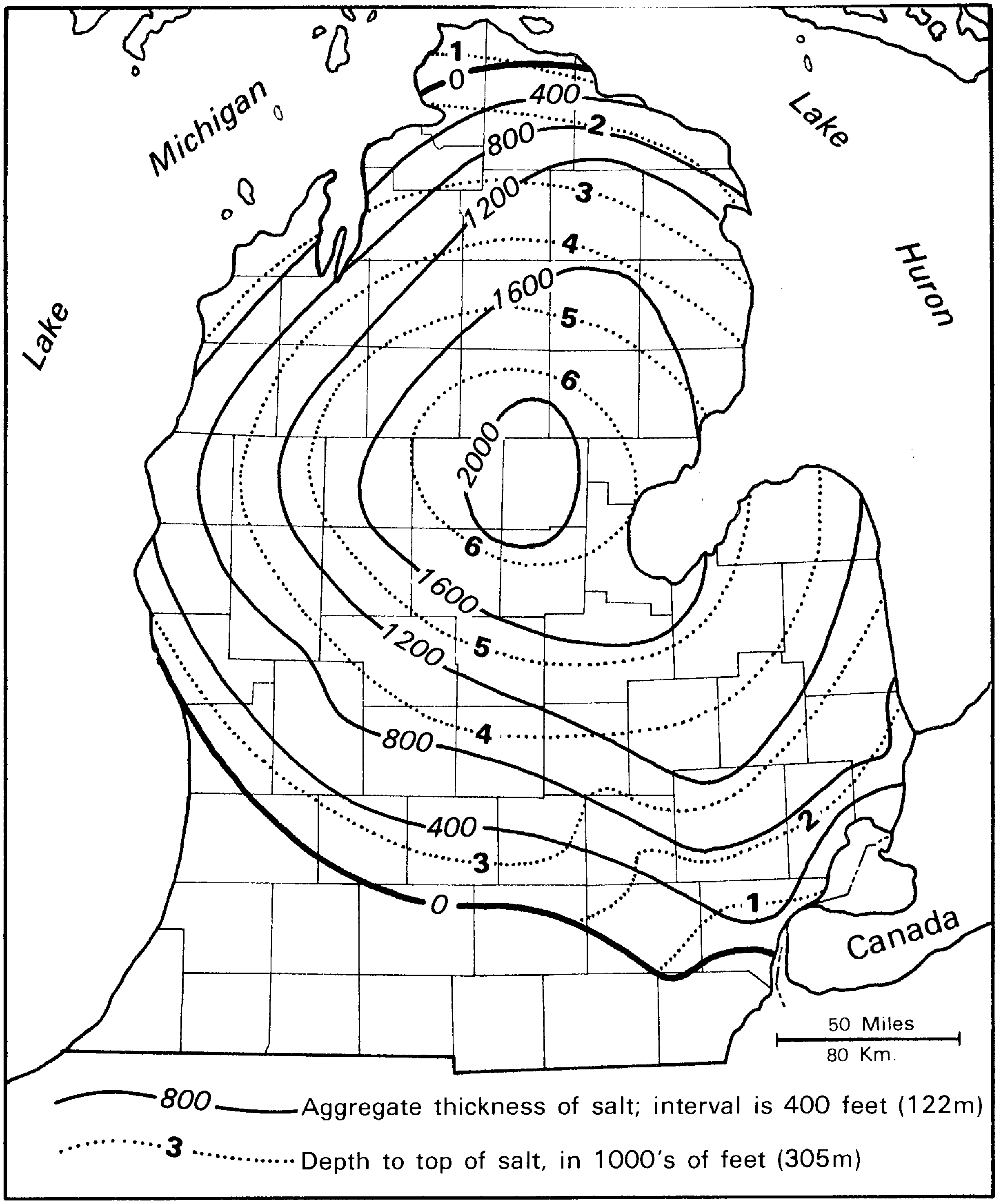
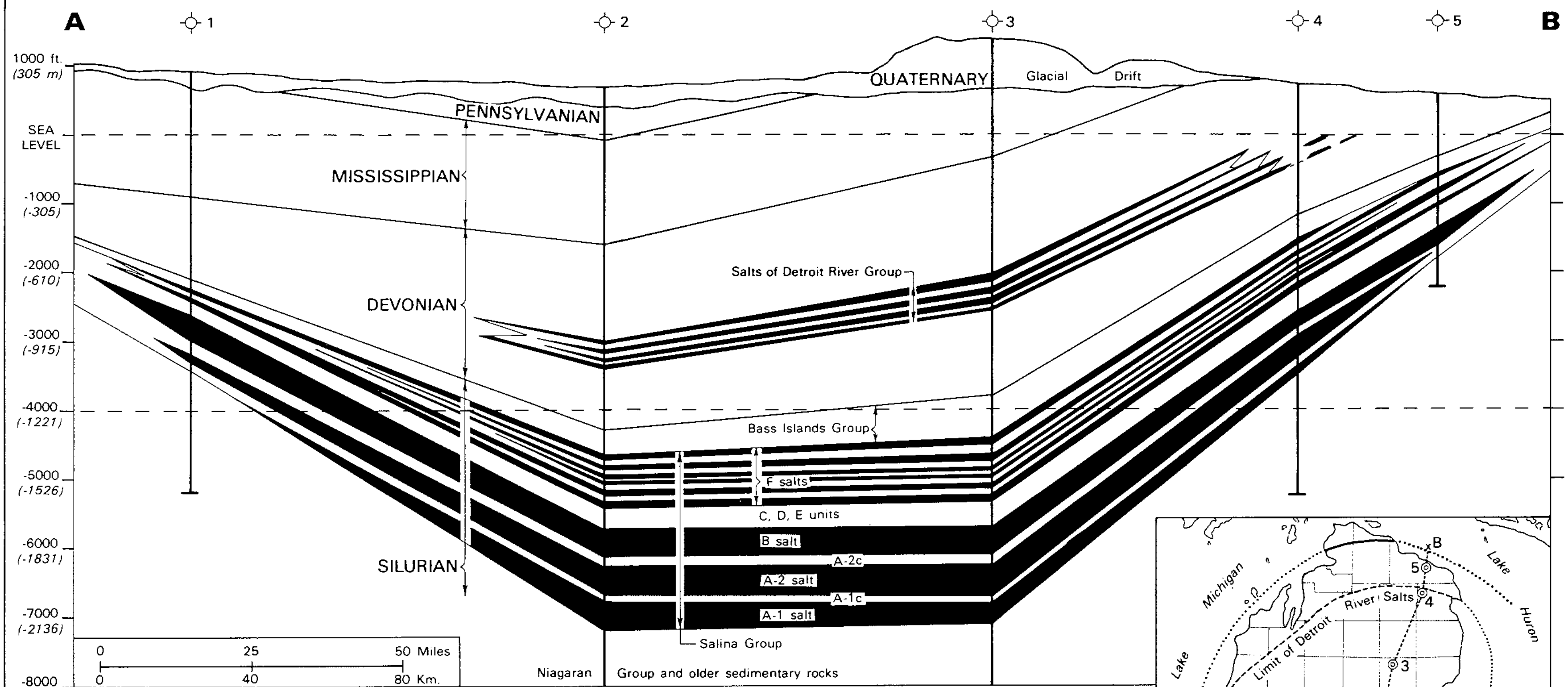
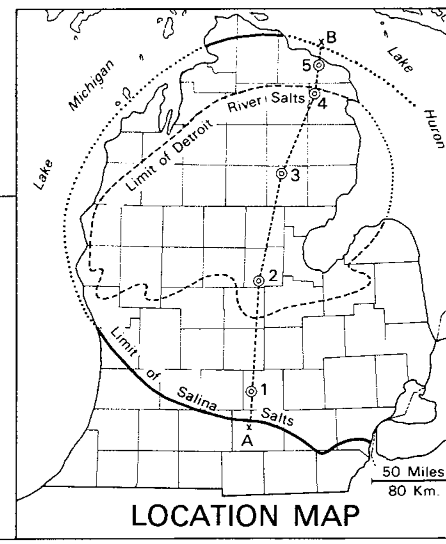


Figure 7. Map showing aggregate thickness in feet and depth to top of salt beds in Salina Group within Michigan basin (modified from Hardenberg, 1949a, 1949b).





LIST OF WELLS USED IN CROSS SECTION

1	Pure Oil Co.	Harkness No. 1	16 - 2N - 2W	Ingham County
2	Pure Oil Co.	Emery No. 1	21 - 13N - 1W	Midland County
3	Brazos-Sun-Superior,	State-Foster No. 1	28 - 24N - 2E	Ogemaw County
4	Shell Oil Co.	Sheldon-State-Wellington No. 1-34	34 - 32N - 5E	Alpena County
5	Shell Oil Co.	U. S. Steel No. 2-1	1 - 34N - 6E	Presque Isle County

Figure 8. Generalized south-north cross section through Michigan basin showing principal salt deposits of Silurian and Devonian age (after Johnson and Gonzales, 1976).

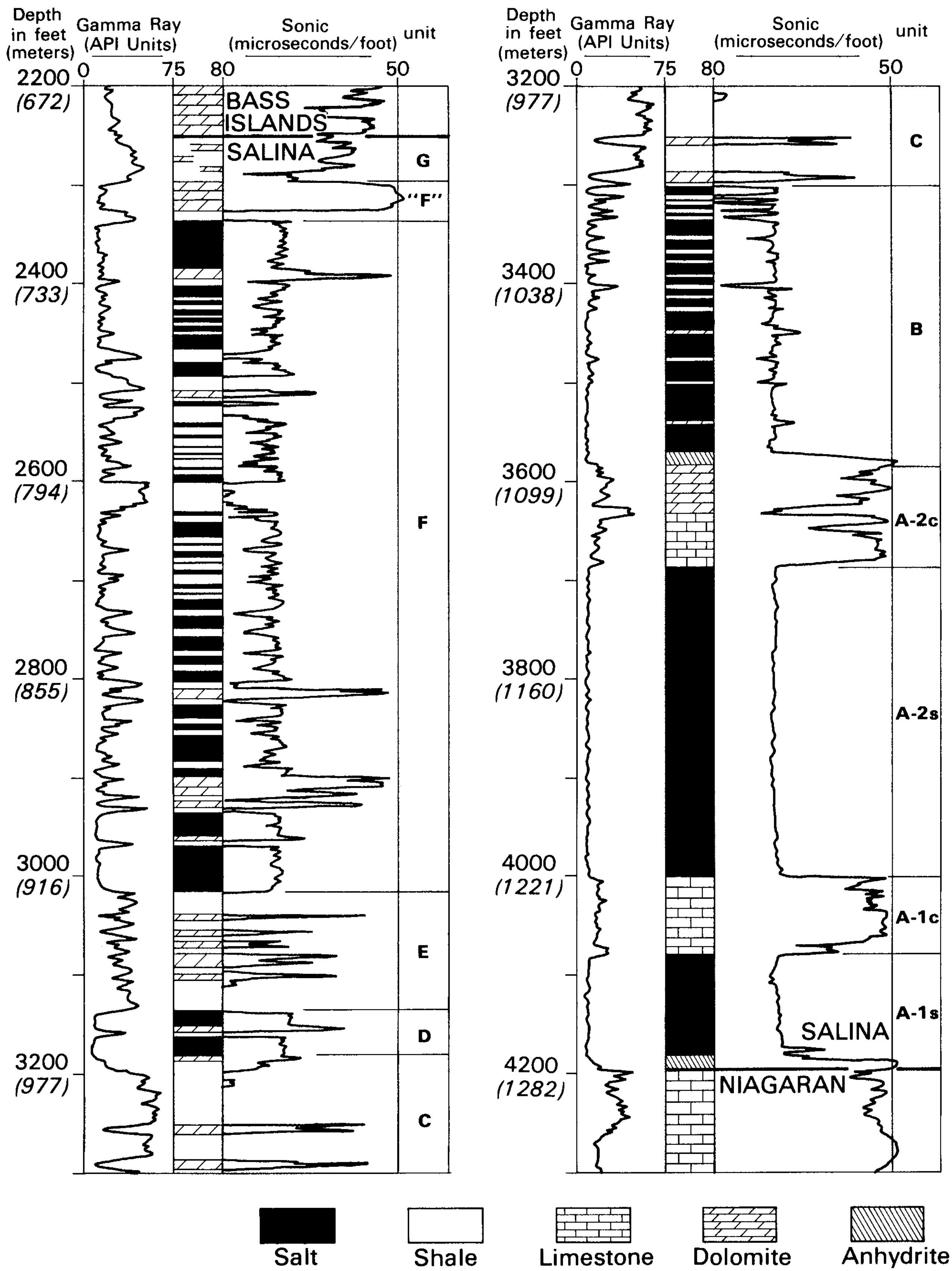


Figure 9. Lithology and mechanical logs of Salina Group near northeast margin of Michigan basin. Logs from Shell Oil Co., Sheldon-State-Wellington No. 1-34, sec. 34, T. 32 N., R. 5 E., Alpena County. Lithology interpreted from mechanical logs and sample log. From Johnson and Gonzales (1976).

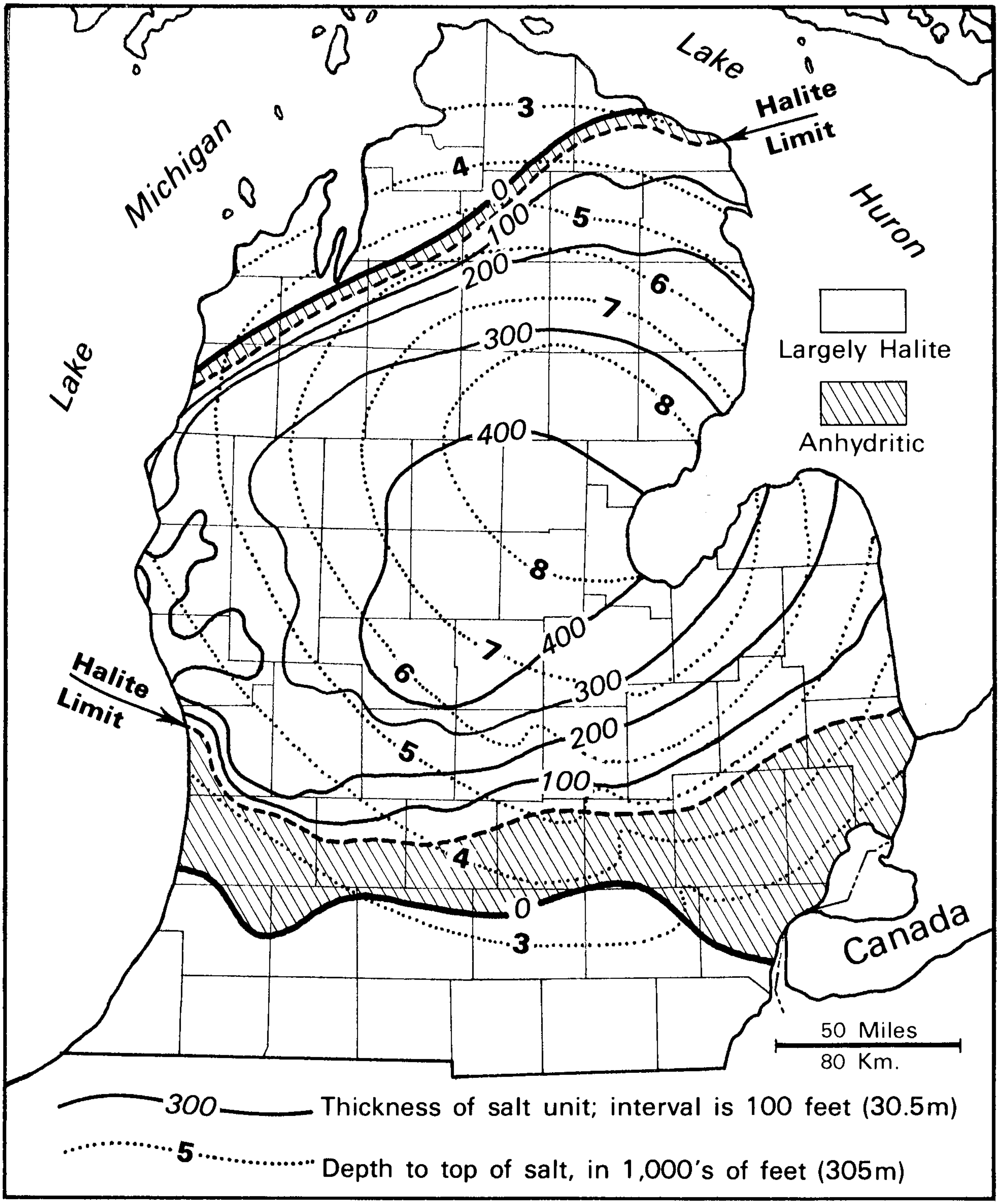


Figure 10. Map showing thickness in feet and approximate depth to top of A-1 salt unit in Salina Group within Michigan basin. Thickness data from Mesolella and others (1974).

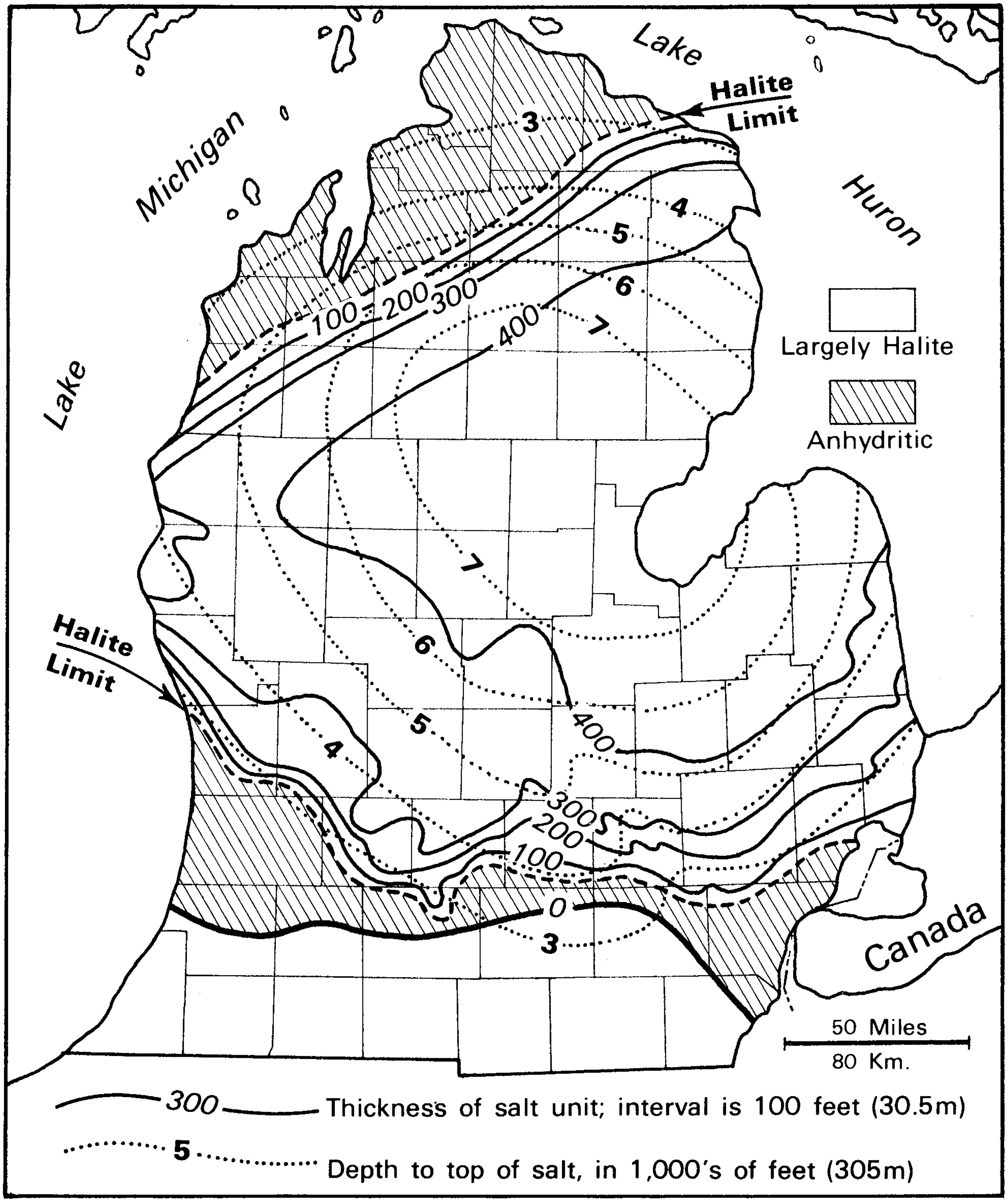


Figure 11. Map showing thickness in feet and approximate depth to top of A-2 salt unit in Salina Group within Michigan basin. Thickness data from Mesolella and others (1974).

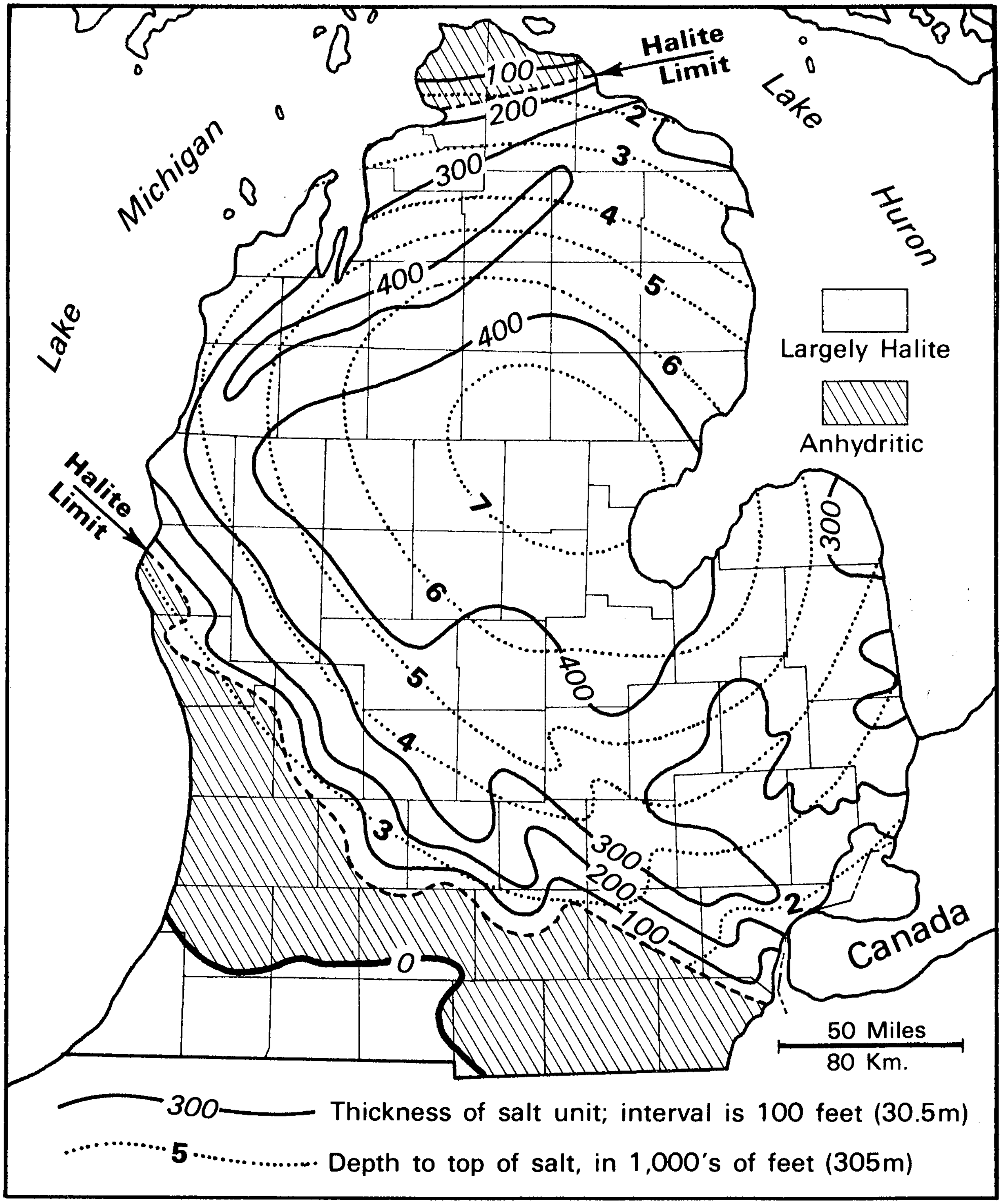


Figure 12. Map showing thickness in feet and approximate depth to top of B salt unit in Salina Group within Michigan basin. Thickness data from Mesolella and others (1974).

F salt. The F unit is a succession of pure and impure salt beds interbedded with shale, dolomite, and anhydrite (fig. 9) and represents the youngest salts of the Salina Group in the Michigan basin.

The F salts, like others in the Salina, are thickest in the central part of the basin. The total thickness of the F unit reaches a maximum of nearly 300 m in Ogemaw County, but the unit thins toward the margin of the basin owing chiefly to depositional thinning of the salt beds (Ells, 1967). In some parts of the basin the salt has been removed by pre-Devonian erosion, and in other areas some of the salts may be thin or missing owing to dissolution by ground water.

Most of the individual salt beds in the F unit are only 2 to 6 m thick, but the two bottom beds and the top bed commonly are massive salts from 10 to 20 m thick (locally as much as 30 m thick).

Inasmuch as the F unit is the shallowest salt in the Salina Group, its depth below ground level is the same as that of the group as a whole (fig. 7). The top of the F salts is less than 900 m deep along the southern and northern margins of the basin.

Detroit River Group

The Detroit River Group of Devonian age contains the youngest salts in the Michigan basin (fig. 8). Salt occurs in many separate units (fig. 13), which are interbedded with anhydrite, limestone, and dolomite (Gardner, 1974). The salt beds are 5 to 25 m thick, although the uppermost salt is 35 m thick in Kalkaska and neighboring counties.

The aggregate thickness of the Detroit River Group salts ranges from 30 to 150 m in much of the northern part of the Michigan basin (fig. 14). The thickness decreases toward the margins of the basin, owing partly to depositional thinning of the salts and partly to dissolution of the salt. The latter process is more prevalent in the northern part of the salt area. The depth to the top of the Detroit River salts is as much as 1,200 m in the central part of the basin, but moderately thick salts lie only 600 to 900 m below the surface in the north.

Salt Dissolution

Natural dissolution of salt beds has clearly occurred within parts of the Michigan basin in the past. Abrupt thinning and termination of some salt units near the perimeter of the basin, and development of salt-core anticlines in the central part of the basin, have been attributed mainly to dissolution of Salina (and perhaps Detroit River) salts during Silurian and/or Devonian time (Landes, 1959; Ells, 1967). Dissolution and removal of the salts caused overlying rock units to become brecciated as they collapsed into the solution cavities, thus forming units such as the Mackinac Breccia, which crops out at the north end of the Southern Peninsula (Landes, 1959).

In addition to areas where dissolution occurred shortly after salt deposition, other areas in the Michigan basin may contain salt beds that are currently being dissolved. Where salt deposits are near the land surface, ground waters can migrate through the surrounding rocks and dissolve the salt. Such waters must continue to move through the system; otherwise, by remaining in contact with the salt, the water becomes saturated, and further dissolution is not possible. The movement of water occurs through aquifers, such as porous layers of limestone, dolomite, and sandstone, and also through fractures, joints, sinkholes, collapse features, and other openings that provide vertical interconnec-

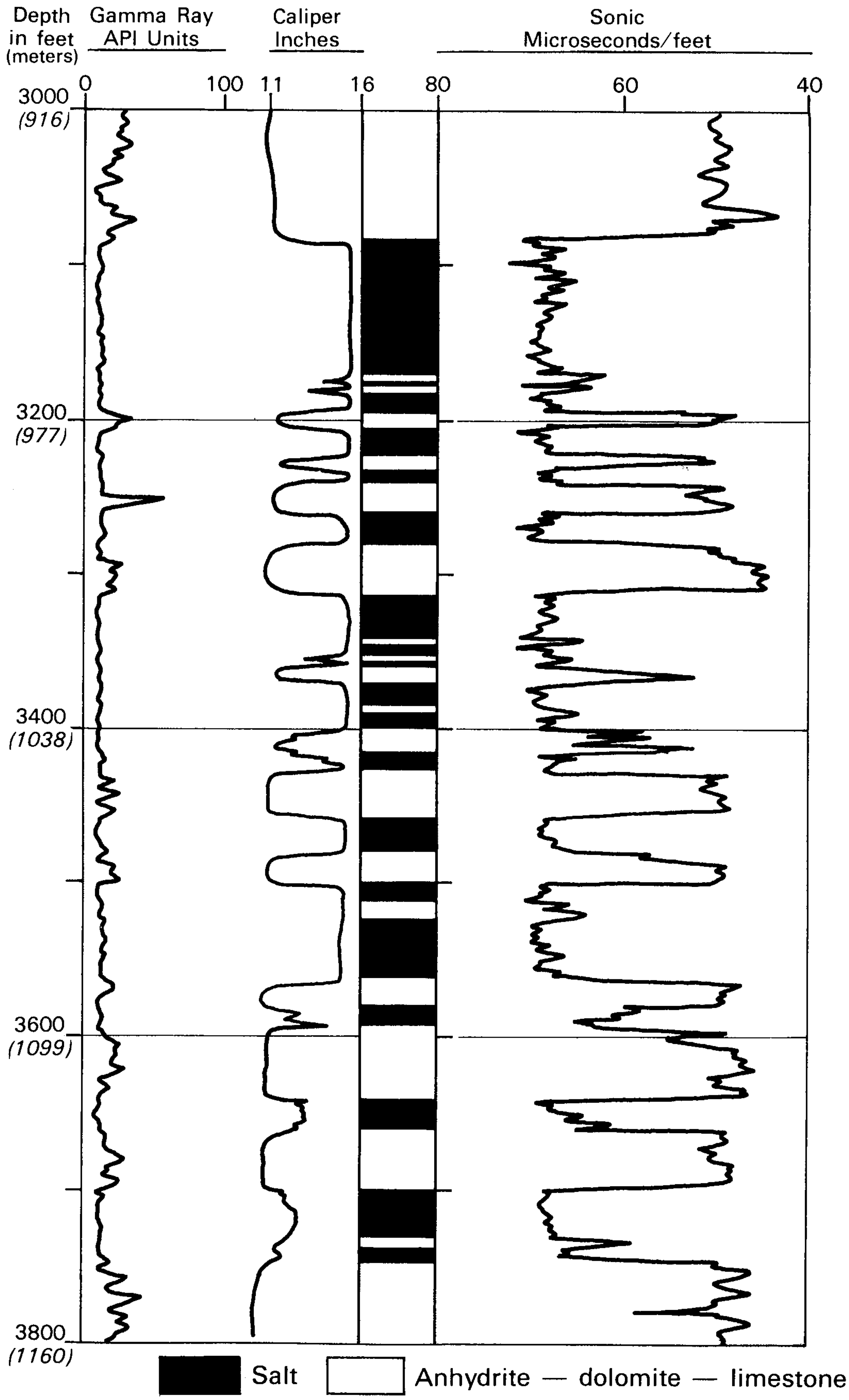


Figure 13. Lithology and mechanical logs of salt-bearing strata in Detroit River Group within Michigan basin. Logs of Shell Oil Co., Shell Kerr No. 1-4, sec. 4, T. 28 N., R. 4 W., Crawford County. Lithology interpreted from mechanical logs. From Johnson and Gonzales (1976).

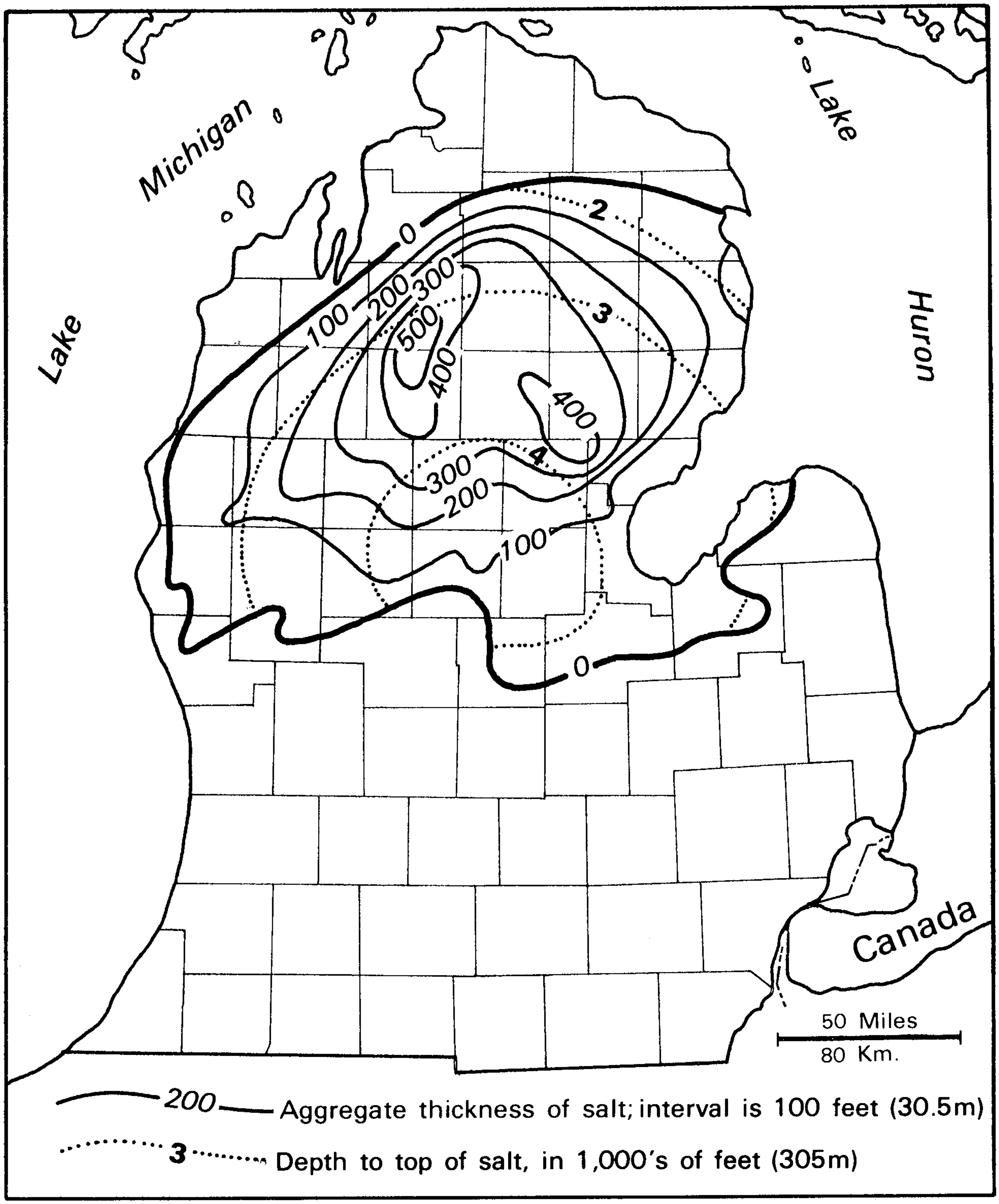


Figure 14. Map showing aggregate thickness in feet and depth to top of salt beds in Detroit River Group within Michigan basin. Modified from Michigan Geological Survey (no date, a, b).

tions between formations. Studies have not yet been carried out on the nature and extent of natural salt dissolution in the Michigan basin, but data now available indicate that dissolution most likely may be occurring in the F salt and possibly the B salt near the perimeter of the basin in the north and southeast and in the Detroit River salt near its limits to the northeast and north. Additional data are needed to establish whether salt is being dissolved in these or other parts of the Michigan basin.

Hydrology

Surface Water

Surface drainage in the Southern Peninsula of Michigan consists of streams and rivers that flow toward Lake Michigan and Lake Huron. The headwaters and drainage areas are within the state, except in the south, where some of the streams flow through parts of Ohio and Indiana. Principal rivers in the state include the St. Joseph, Grand, Muskegon, Manistee, and Au Sable Rivers. Numerous lakes also are present in the Lower Peninsula.

Nearly all the water in streams, rivers, and lakes comes directly from precipitation and runoff, but some is derived from springs emerging from glacial drift and bedrock. Small amounts of excess or used water produced from water wells add slightly to the discharge. Average annual precipitation ranges from 66 to 92 cm: it is 66 to 76 cm in most parts of the northeast and is 76 to 92 cm in most of the southwest.

Water from the Great Lakes is used extensively by municipalities and industries located near these water bodies. Inland from the Great Lakes, the many lakes and rivers are a major source of fresh water for municipal, industrial, and rural use.

Ground Water

In most parts of the Southern Peninsula that are remote from Lake Huron or Lake Michigan, glacial drift is the common source of fresh ground water for urban, industrial, and rural water supplies. Where the drift, which ranges in thickness from 15 m to more than 250 m in most parts of the state (fig. 5), is thick and chiefly consists of sand, it is easily recharged by precipitation. In those areas, large volumes of fresh ground water are stored and water wells provide good yields for long periods of time. Where the drift is thin or consists mostly of clay, little water infiltration occurs, and well yields are small or nonexistent.

The yields of water wells in glacial drift range from 35 lpm (liters per minute) to more than 1,875 lpm in many parts of the Southern Peninsula (Twenter, 1966a). The areas of highest yield generally coincide with the areas of thickest drift. Yields of less than 35 lpm can be expected in several large areas of thin drift in the south-central, east-central, and northern parts of the region.

Water in the glacial deposits is generally of good quality but is moderately hard. Total dissolved solids commonly range between 200 and 500 ppm (parts per million), and hardness (expressed as $CaCO_3$) ranges between 175 and 350 ppm (Piper, 1972). In the lowest part of the drift, or through most of its thickness where the drift is thin, water quality decreases owing to an increase in calcium (Ca) and sulfate (SO_4) ions and, locally, in sodium (Na) and chloride (Cl) ions. This increase in dissolved solids near the lower part of the drift results from mixing between the more saline waters of the underlying bedrock and the fresh waters in the drift.

Limestone, dolomite, and sandstone bedrock underlying the glacial drift provides fresh ground water in some parts of the Southern Peninsula, particularly in the south-central, east-central, and northeast areas (Twenter, 1966b). Yields of less than 375 lpm are fairly common, but a few wells have recorded yields greater than 1,875 lpm. The higher yields are commonly from sandstones and some of the limestones, whereas the lowest yields (less than 35 lpm) are from the shales.

Principal bedrock aquifers in the Southern Peninsula include the Saginaw Formation (Pennsylvanian) and the Marshall Sandstone (Mississippian) in the south-central and eastern parts of the region and a series of Devonian limestones and dolomites (Traverse Group, Dundee Formation, and Detroit River Group) in the northeast. These and other bedrock aquifers yield ground water of good quality at many places where they are within 100 m of the land surface, and in all parts of the basin they are at shallower depths than the underlying thick salts.

All bedrock formations in the basin contain saline or mineralized water at depth. The base of the fresh-water zone in these aquifers ranges from less than 60 m to more than 270 m in different areas. Below these depths, the water is generally too saline for any practical water-related use. Natural brines are, however, commercially obtained in certain areas and are processed for mineral commodities.

Another geohydrologic application that has been widely instituted in the Michigan basin is the development of industrial-waste-disposal wells (Ives and Eddy, 1970; Warner and Orcutt, 1973). Subsurface saline aquifers, where sufficiently permeable and thick and overlain by an effective impermeable seal, have been utilized for disposal through injection of a variety of process brines, chemical effluents, and other liquid wastes. In fact, the first industrial-waste-disposal well approved and regulated by a state was installed in Michigan in 1950. Several different disposal zones within the Paleozoic rock sequence have been utilized; the largest concentration of these disposal systems is in the Midland area.

Based on the foregoing dicussion, it is clear that in the Michigan basin the important fresh-water aquifers are in glacial drift and in certain sandstones, limestones, and dolomites at shallow depths. Good-quality water thus is separated from the deeper, underlying salt deposits in all parts of the basin. Water present at depths greater than several hundred meters is commonly too saline for most uses.

Seismic Activity

Recorded seismic activity in the Michigan basin and surrounding areas is low, compared to most other parts of the United States. Earthquakes having a Modified Mercalli Intensity of V (MM V) or greater are sparse in the region (Coffman and von Hake, 1973), except in northwestern Michigan and in western and northeastern Ohio (fig. 15). Earthquakes in nearby parts of Canada with an Instrumental Magnitude of 3.5 (M_L 3.5) or greater are sparse, according to Smith (1966). The entire Michigan basin is within zone 1 (expected minor damage) on the seismic-risk map prepared by S. T. Algermissen (ESSA/Coast and Geodetic Survey, 1969) (fig. 16).

The four earthquakes of MM V or MM VI recorded in Michigan's Lower Peninsula occurred in the south (Coffman and von Hake, 1973), and only two of them occurred in the area underlain by salt. Earthquakes were observed near the head of Saginaw Bay in 1872 (MM V), in southeast Michigan in 1877 (MM IV-V), near Kalamazoo in 1883 (MM VI), and in south-central Michigan in 1947 (MM VI). Other earthquakes recorded in

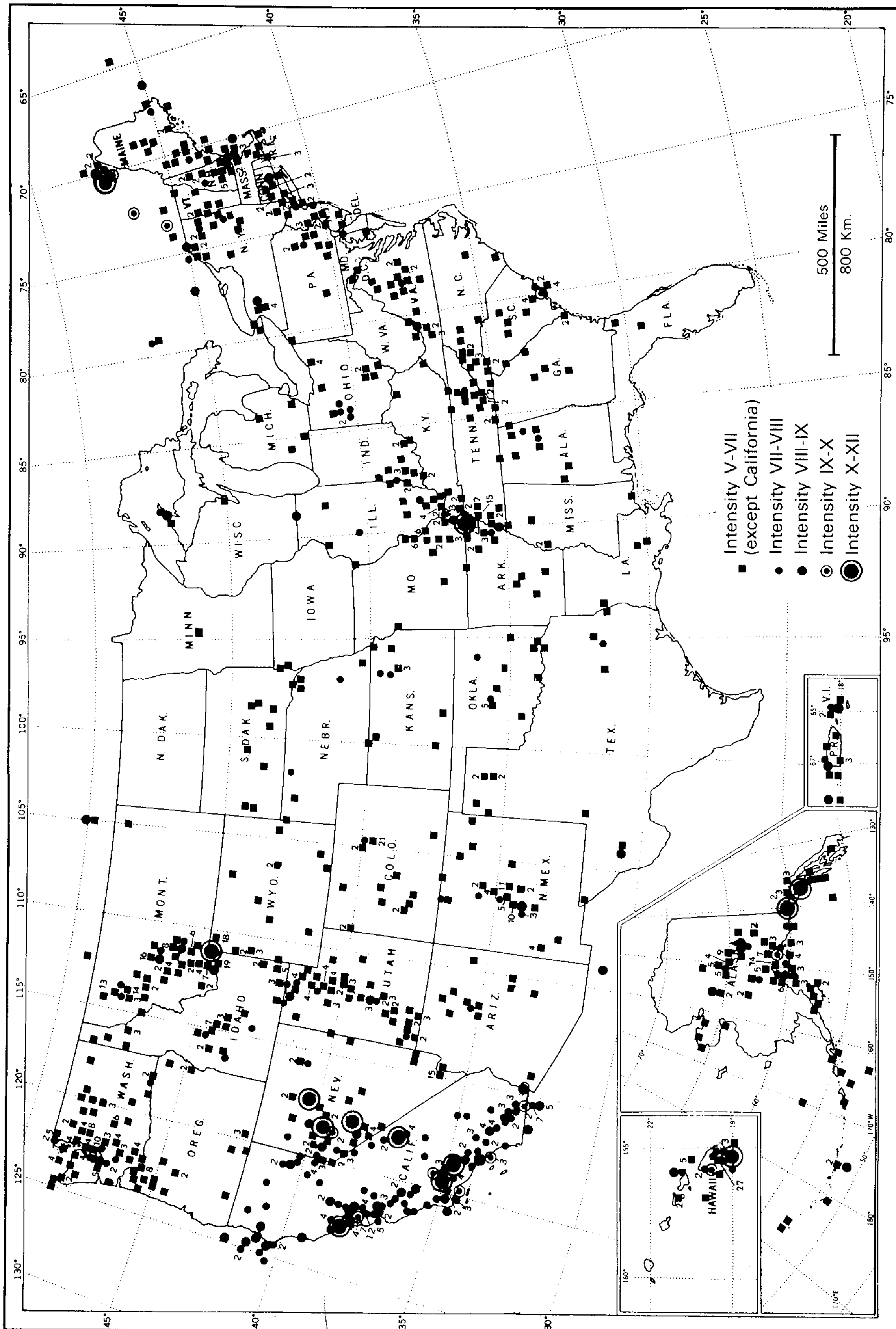


Figure 15. Map of United States showing earthquakes of Modified Mercalli Intensity V, or greater, through 1970 (after Coffman and von Hake, 1973).

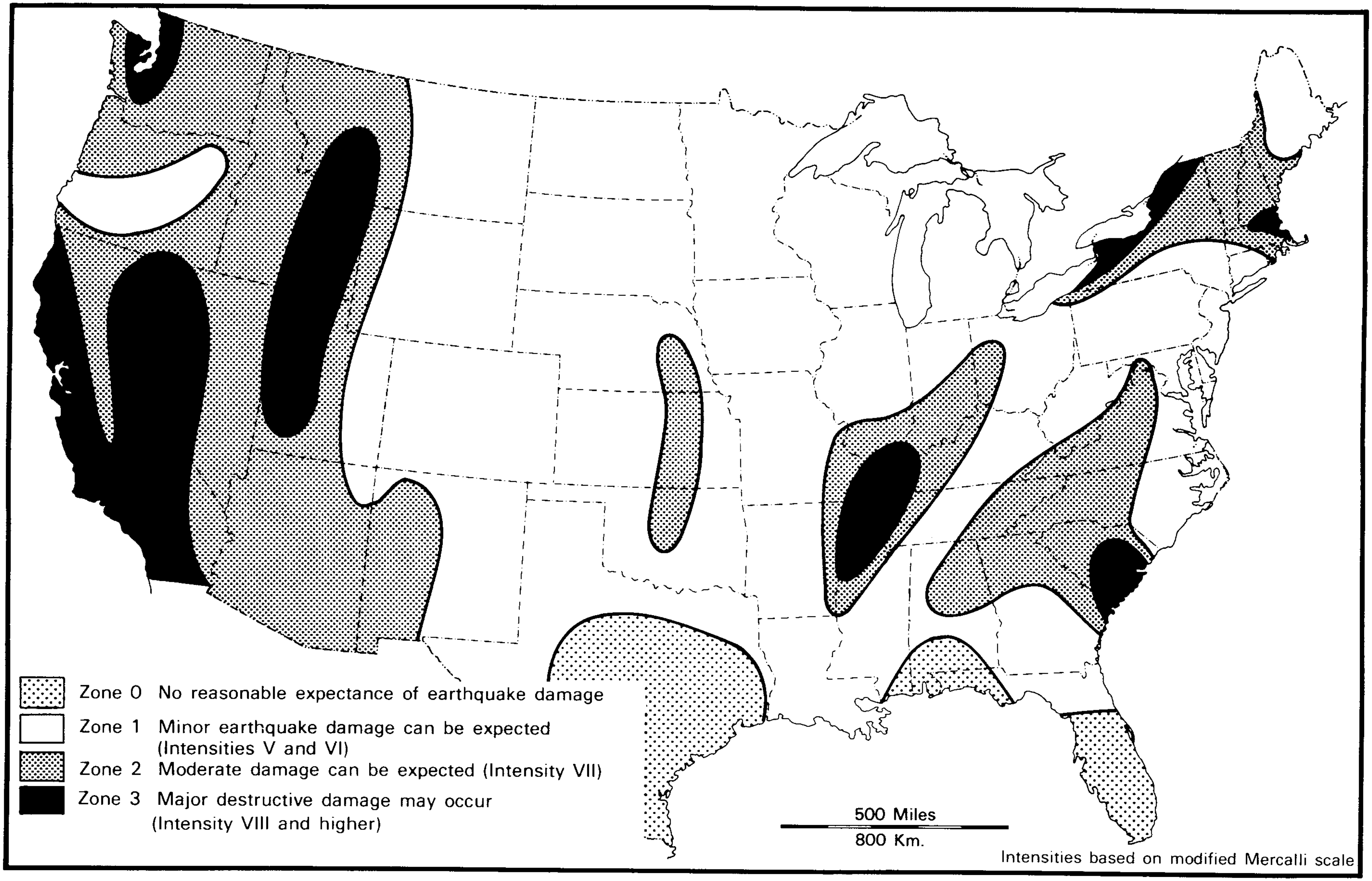


Figure 16. Map showing seismic-risk zones in United States (after ESSA/Coast and Geodetic Survey, 1969).

Michigan were located in the Upper Peninsula and include events at Menominee in 1905 (MM V), at Calumet in 1905 (MM VI), on the Keweenaw Peninsula in 1906 (MM VIII), and at Houghton in 1909 (MM V).

The larger earthquakes in nearby Canada include events during 1947 near Sudbury (M_L 4.4), near Laforest (M_L 4.3), and in Georgian Bay (M_L 4.5); a later event occurred in 1957 near London (M_L 4.2).

The low level of recorded seismic activity in the Michigan basin indicates that earthquakes should not be a special problem in considering the area for waste storage.

Mineral Resources

Oil and Gas

Oil and gas are produced in the Michigan basin from reservoir rocks of Ordovician, Silurian, Devonian, and Mississippian age (Ells and others, 1974; Netherland, Sewell and Associates, 1975b). Most of the oil and gas fields in central and southwestern Michigan produce from reservoirs above the Silurian salt deposits (fig. 17). These fields generally produce from structures located along salt-core anticlines that trend northwest to southeast. More than 20 major anticlines are present in this part of the state. Many dry holes have been drilled along these folds in order to connect the productive areas, and in recent years drilling in this province has decreased.

Fields producing from Silurian (Niagaran) reefs are concentrated in distinct bands or clusters: one is the northeast-southwest band across the northern part of the Lower Peninsula, another is the east-west band across the south-central part of the state, and the third is a cluster in the southeast. The fields in these bands are prolific and produce from pinnacle reefs that developed in the shelf area that rimmed the Michigan basin in Niagaran time. Reefs have not been found in the central part of the basin, where the northwest-southeast-trending post-Silurian fields are located.

The first commercial oil well in the pinnacle reefs of the northern part of the Lower Peninsula was completed in 1952 in Mason County (Mesolella and others, 1974). Other tests that penetrated the Niagaran and Salina carbonates commonly exhibited noncommercial shows of hydrocarbons. In 1969, however, three exploration wells confirmed the presence of commercial quantities of petroleum within Niagaran reefs, and this precipitated a drilling boom that resulted in completion of many commercial oil and gas wells within the northeast-trending band of reefs. The "fairway" in which the pinnacle reefs occur is about 15 km wide and now extends 250 km from Mason County on the southwest into Presque Isle County, where several recent discoveries have extended the northeast limit of this trend.

Fields producing from Ordovician reservoirs are near the southern border of the state, and they generally lie outside the area underlain by thick salts in the Salina Group.

Although a considerable number of oil and gas tests have been drilled in Michigan, most are concentrated in specific areas and along specific trends (Netherland, Sewell and Associates, 1975b). Large parts of the Michigan basin contain only a few boreholes, and there are other large areas where no wells (other than shallow water wells) have been drilled. Thus there are sizable areas, some around the perimeter of the basin, underlain by thick salt deposits where the oil and gas potential is low and where the use of salt for waste-storage purposes would not conflict with petroleum development.

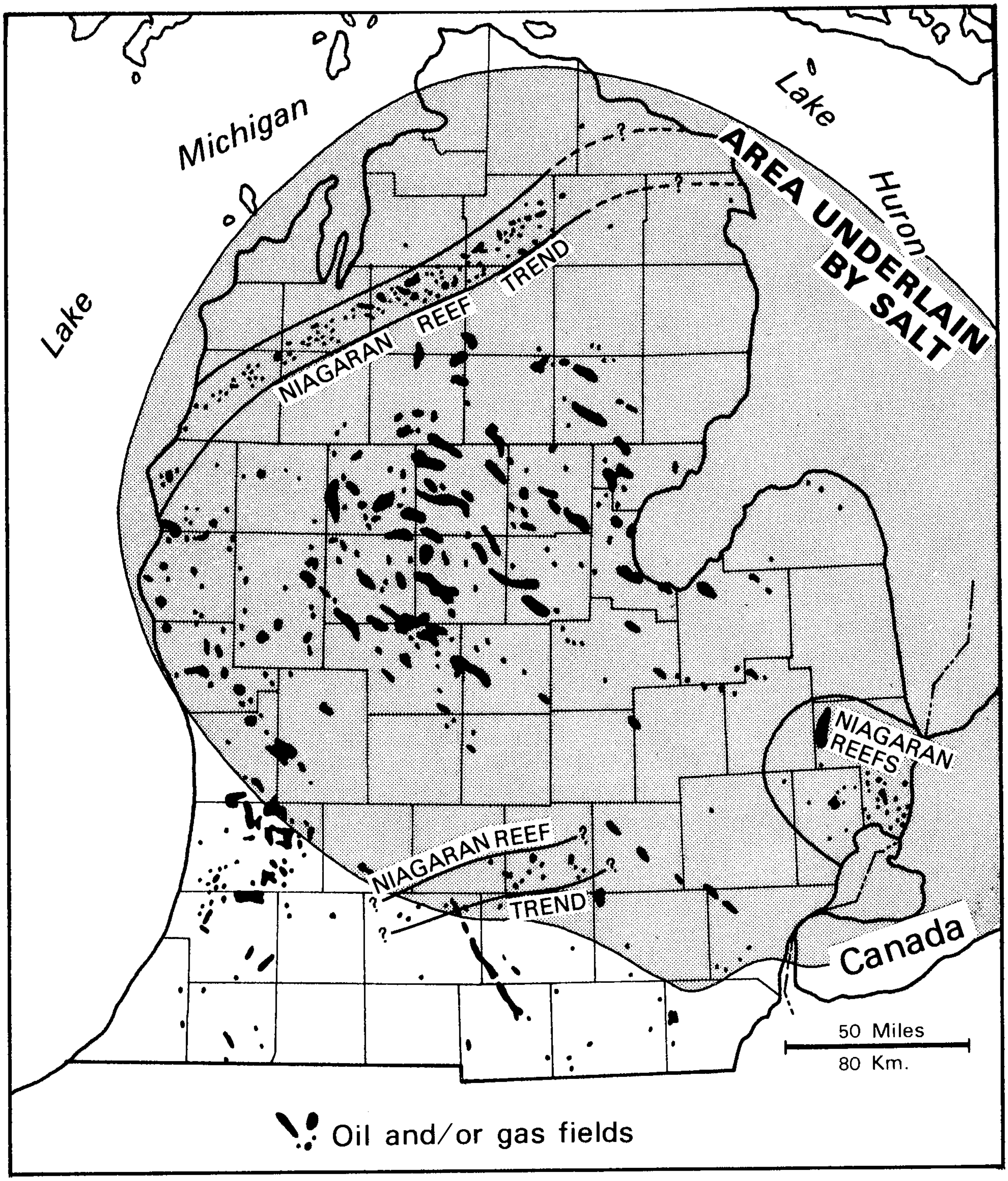


Figure 17. Map showing oil and gas fields in Michigan (after Ells and others, 1974; Netherland, Sewell and Associates, 1975b).

Salt

The salt resources of Michigan are vast and are limited stratigraphically to the Silurian (Salina Group) and Devonian (Detroit River Group) Systems. Salt or salt brines are produced at mines or brine-well plants at 10 localities in the southern and central parts of the state (fig. 6). In the southeast 3 operations are active in Wayne County and 2 in St. Clair County; in the center of the state 1 producer each is located in Midland and Gratiot Counties; and in the west there are 2 facilities in Manistee County and 1 in Muskegon County.

International Salt Co.'s Detroit mine in Wayne County is the only place where rock salt is being mined in Michigan. Two beds of salt 6 and 9 m thick in the F unit are mined at depths of about 300 to 330 m. Mining in the nearly horizontal salts is by the room-and-pillar method, with rooms and pillars both being about 18 m square. Although the mine has been in operation since before 1900, the pillars show no indication of deformation from overburden pressure nor has any water seeped into the dry mine from adjacent rock units. Two other rock-salt mines in the southeast part of the Michigan basin are in Canada (fig. 6): Canadian Salt Co. (Morton) operates a mine just across the Detroit River from the International Salt Co. mine, and Sifto Salt Co. (a Domtar subsidiary) is about 150 km to the northeast at Goderich, Ontario.

The other salt plants in Michigan are brine-well operations. Detroit River salts are solution mined in Manistee County, in the west, whereas the Salina salts (B and F units) are being dissolved at the other brine-well locations. Some of the earlier formed solution cavities, as well as new ones being formed in the southeast near Detroit, are now being used for underground storage of liquefied petroleum gases (LPG).

Salt mining and brine wells are grouped in specific areas of the basin, such as in the southeast, central, and west, but elsewhere there are thick salts at moderate depths without a past history of mining activity. Thus there are salt deposits in the basin that can be used for waste storage that are far removed from solution caverns and mines. And with the vastness of salt resources in the state, the possible use of underground salt beds for radioactive-waste storage at one or more sites would not make a significant impact on the present or future availability of adequate salt resources for this part of the United States.

Natural Brines

Natural brines or salt water produced from deep wells in the state have been a commercial source of such important chemicals as bromine, iodine, calcium chloride, and magnesium compounds (Lewis, 1975). The principal source beds for these brines are the Filer and Sylvania Sandstones in the Devonian Detroit River Group; thus, these units are younger than the Salina salt beds.

Michigan currently ranks first among the states in production of such natural brines. The 7 operating plants are located across the central part of the state in the following counties: Lapeer (1 plant), Midland (1), Gratiot (1), Mason (2), and Manistee (2).

Other Minerals

Other known mineral resources in Michigan either are not commercially recoverable in areas that might be considered for radioactive-waste storage or are being developed only by surface-mining techniques that would not conflict with radioactive-waste storage at depth.

Major metallic resources of iron ore and copper are recovered only in the Upper Peninsula, and thus the continued development of these reserves would not conflict with use of the salt deposits in the Lower Peninsula.

Gypsum resources of the state are great and occur mainly in the Michigan Formation (Mississippian) and in the Detroit River Group (Devonian) (Briggs, 1970); thus they are younger than the Salina salt sequence. Five companies are producing gypsum; 3 quarries are active near Alabaster in Iosco County, and 2 shallow mines are operated near Grand Rapids in Kent County (Lewis, 1975).

Potash has been identified in the A-1 evaporite (Anderson and Egleson, 1970; Matthews, 1970; Matthews and Egleson, 1974), but it is apparently restricted to the central part of the Michigan basin, where the A-1 salt and the overlying A-2 and B salts are quite deep. These potash deposits are not now being produced.

Stone is an important nonmetallic mineral resource that is produced from bedrock formations for a variety of uses. Limestone and dolomite are used as crushed stone for aggregate, cement, lime, flux, and for chemical and agricultural application. They also are worked for dimension stone. Other types of stone, such as sandstone, basalt, and marble, are used primarily as aggregate and dimension stone. The many stone quarries in the Southern Peninsula are concentrated in the southeast, the north, and in the Saginaw Bay area.

Shale and clay deposits are widely distributed in Michigan's Southern Peninsula (Lewis, 1975). This resource, which occurs both in the bedrock and in the glacial drift, is used in the manufacture of cement, brick, drain tile, sewer pipe, and flowerpots. Ten companies operate open pits in the southeastern, central, and northern parts of the Southern Peninsula.

Sand and gravel probably constitute the most widespread mineral commodity in the state (Lewis, 1975). Most commercial deposits have been developed in glacial deposits, such as outwash material, kames, eskers, and glacial-lakeshore sediments. Some of the resource is obtained from river terraces and deltaic deposits. More than 350 companies are producing sand and gravel from open pits in all parts of the state, and most of these pits are near the expanding urban areas in the south.

These various resources are being extracted chiefly from surface mines, and storage of waste in underlying salt beds should not conflict with such development.

Regional Evaluation for Storage of Radioactive Waste

As a result of this study of the Michigan basin, and the earlier studies by Briggs (1968), Landes (1972), Landes and Bourne (1976), and Johnson and Gonzales (1976), the Lower Peninsula of Michigan appears to have a geologic framework and a series of salt deposits that may be suitable locally for the underground storage of high-level radioactive waste. Thick deposits of massive rock salt (halite) are present at moderate depth; they are nearly flat lying and have not been structurally deformed or fractured in most parts of the basin. The region is characterized by tectonic stability. There have been few recorded earthquakes of MM V or greater in areas underlain by salt, and the entire state of Michigan lies within seismic-risk zone 1 (minor damage).

In addition to these regional characteristics that make the basin appear generally favorable, there are other geologic-hydrologic factors that bear upon the overall potential of the Michigan basin for possible repository consideration. Glacial drift is thin or absent in large areas of the basin, and similarly there are many areas that are not underlain by important fresh-water resources. There also are large regions with few boreholes and low petroleum potential, and substantial areas free of brine wells or salt mines.

Upon review of available data, it appears that many of the previously mentioned favorable characteristics are met in the north part of the basin, particularly in the northeast. Here, the A-2, B, and F salts locally are thick and occur at moderate depths. Thick Salina salts also are present at moderate depths locally in the southeast, but this area has many oil and gas fields developed in pre-Salina rocks (mainly Niagaran reefs) and is close to the Detroit metropolitan area.

The Detroit River salts are thick and at moderate depths in parts of north-central Michigan. Several factors that need to be weighed and studied in more detail in this area, however, include thick glacial drift, important ground-water supplies, and petroleum production from the Niagaran-reef trend that crosses this area. Additional special studies are needed to evaluate these factors.

APPALACHIAN BASIN

Structure and Geologic Framework

The Appalachian system, the dominant tectonic feature in the eastern United States, consists of several structural belts that can be traced from northern Alabama through the New England states. Present are a great thickness of Cambrian through Permian sedimentary rocks in the western part (Appalachian basin) and a large volume of metamorphic and igneous rocks in the eastern part (Blue Ridge and Piedmont provinces).

The undeformed portion of the Appalachian basin being considered in this report is an elongated sedimentary and structural basin that extends northeastward from Tennessee across parts of Kentucky, Virginia, West Virginia, Ohio, Maryland, Pennsylvania, and New York (figs. 2, 3). This regional feature is bordered on the west and north by the Cincinnati-Findlay-Algonquin arches and the Adirondack uplift and on the east by the tightly folded and faulted Valley and Ridge province. The basin contains a southeastward-thickening prism of sandstones, limestones, shales, and salts that aggregate 2,000 to 7,000 m in thickness and that are characterized by low dips (less than 1°) and some gentle folds. Comprehensive discussions of the Appalachian basin as part of the stable interior of North America were given by Woodward (1958), Roth (1968), and Colton (1970).

Sedimentation in the basin occurred throughout the Paleozoic Era and culminated at the end of this time with the final major orogeny (the Appalachian "revolution") that determined the present geologic pattern. Salt deposits in the basin are Late Silurian in age and connect with the Salina salts of the Michigan basin to the northwest through the Chatham sag (a low place between the Findlay and Algonquin arches).

The Salina Group consists of a series of salts, dolomites, anhydrites, and shales deposited in an extensive sea that covered most parts of the Appalachian basin. Some workers (Alling and Briggs, 1961; Fergusson and Prather, 1968) suggested that partial restriction of marine waters during Salina time was accomplished by earlier growth and development of Middle Silurian reefs within the Lockport Formation (Niagaran Series) parallel to the perimeter of the basin. The eastern limit of the salts in parts of the basin was controlled by the influx of clastic material from the east side of the basin. Clifford (1973), however, stated that the Niagaran reefs did not exercise any control on conditions leading to evaporite deposition in the Ohio portion of the basin, and both Rickard (1969) and Clifford (1973) felt that the nature of the restrictive structural elements for the Appalachian basin is uncertain.

Salina salts in the Appalachian basin formed by precipitation of halite onto the floor of a relatively deep basin (Rickard, 1969; Clifford, 1973). Slow replenishment of sea water to the basin allowed the accumulation of thick sequences of rock salt over vast areas. Marine transgressions diluted the saline waters, and during these times the normal-marine sediments were deposited.

Directly overlying the Salina Group in Ohio is the Late Silurian Bass Islands Dolomite (Clifford, 1973). At various places farther east, in Pennsylvania and New York, the overlying units are the Rondout, Cobleskill, and Helderberg limestones (Rickard, 1969). Younger Devonian, Mississippian, Pennsylvanian, and Permian deposits are chiefly clastics and comprise the outcropping rock units in all areas underlain by the salts. Many of the post-Silurian sandstones contain oil and gas, and major bituminous coal resources are being mined from Pennsylvanian-aged rocks in parts of Ohio, Pennsylvania, and West Virginia.

Glaciers covered large parts of the northern end of the Appalachian basin during Pleistocene time. In much of this area the drift is thin, although locally it is more than 100 m thick.

Principal structural features affecting Silurian and younger strata are lacking in most shallow parts of the Appalachian basin in the north and northwest where the Salina salts are at favorable depths. Structural mapping by Rickard (1969) and Clifford (1973) indicate no faults or major folds in these areas. Farther southeast, however, and even in parts of south-central New York, the post-Silurian rocks are broadly folded and locally faulted, and the intensity of folding increases toward the deeper part of the basin.

There is significant seismic and subsurface evidence that some of the post-Silurian folds resulted from décollements that extend down into the Salina salts and that the pre-Salina sediments have not been affected by these structures (Frey, 1973). Frey also showed that the Salina salts thicken in the core of the anticlines and are thin in the adjacent synclines. Although these salt-core anticlines are generally in the deeper part of the basin, they apparently extend northward into south-central New York where the Salina salts are less than 900 m below the surface. Jacoby (1963), Prucha (1968), Chute (1972), and Jacoby and Dellwig (1974) described deformation of salt beds about 500 to 600 m below the surface in mines and brine fields in Yates, Schuyler, and Tompkins Counties, New York.

The major episode of tectonic activity in the Appalachian system was the Late Paleozoic Appalachian "revolution," when rocks of the eastern area were intensely folded and faulted. This deformation becomes less intense westward and was mild or absent in most of the area where the Salina salts are at shallow depths. The area has been tectonically stable since the Appalachian "revolution." Glacial rebound has occurred in the region since final retreat of the great ice sheets, but it does not constitute a deformational hazard.

Data available on sediment loads of the streams draining the study area (Great Lakes Basin Commission, 1975) indicate that the rate of denudation would be about 50 to 100 m over the next several hundred thousand years. The integrity of radioactive wastes buried at moderate depths below the present-day land surface would thus be maintained over a sufficiently long period of time.

Salt Deposits

Salina Group

Thick, high-purity salt deposits of the Appalachian and Michigan basins underlie about 250,000 sq. km of the northeastern United States (fig. 6) and represent one of the greatest accumulations of salt in the world (Pierce and Rich, 1962; Lefond, 1969). Rock-salt deposits of the Appalachian basin are all in the Salina Group of Late Silurian age. The Salina is a sequence of interbedded salt, dolomite, and shale beds that can be correlated over large areas. Major subdivisions of the Salina can, in fact, be correlated with units in the Michigan basin (Fergusson and Prather, 1968; Rickard, 1969; Clifford, 1973). Recognition and correlation of individual units over such a large area is greatly enhanced by the distinctive mechanical-log curves recorded for each unit in oil and gas tests.

The thickness of the Salina Group is typically between 150 and 500 m where it is in the shallow subsurface, but it increases to the southeast into the basin and reaches a maximum of more than 750 m in the deep subsurface of north-central Pennsylvania (Rickard, 1969). In addition, the aggregate thickness of salt in the Salina increases from 30 to 60 m in the shallow parts of the basin to more than 150 m in south-central New York and north-central Pennsylvania (figs. 18–20).

Landes (1945) originally established the major subdivisions of the Salina Group in the Michigan basin. The same subdivisions were later recognized in Ohio (Ulteig, 1964), and the interbasin correlations are now well established through the work of Rickard (1969) and Clifford (1973). Salt is restricted to the B, D, E, and F units in the Appalachian basin. Composite sections of the Salina Group are presented in figure 21 for northeast Ohio and south-central New York, where thick salts are present at fairly shallow depths. The reports by Rickard and Clifford are the prime sources of data for the following descriptions.

B unit. The B unit contains the oldest (deepest) salts in the region and rests conformably upon the shales, dolomites, and anhydrites of the underlying A unit of the Salina Group (fig. 21). Consisting of interbedded salt, shale, dolomite, and anhydrite, the B unit is typically 15 to 50 m thick.

The highest of the salt beds in the B unit in New York appears to be the thickest and purest; it is commonly 5 to 6 m thick and is mined at Retsof by the International Salt Co. Other salt beds are typically 1 to 6 m thick in New York, Pennsylvania, and Ohio.

Distribution of salt in the B unit is limited to the shallow part of the basin—in western New York, the northeast corner of Ohio, and adjacent parts of northwestern Pennsylvania (Rickard, 1969). The only area where the aggregate thickness of salt in the B unit exceeds 30 m is in Lake and Ashtabula Counties, Ohio, where the top of the B salt is 600 to 750 m below land surface. The aggregate thickness of salt is 15-30 m in a larger area of northeastern Ohio and adjacent Pennsylvania and also in several western New York counties, such as Ontario, Livingston, Wyoming, Allegany, and Cattaraugus (Rickard, 1969).

D unit. The D unit contains two or more moderately thin salt beds interbedded with shale (fig. 21). The total thickness of this unit typically ranges from 10 to 40 m, but the salts may be thick enough for radioactive-waste storage locally in parts of Steuben, Schuyler, Yates, and Chemung Counties of south-central New York (fig. 18).

E unit. The E unit is characterized by shale and dolomite, but it locally contains one or two thin beds of salt in the middle of the unit (fig. 21). The total thickness of the E unit is commonly 15 to 60 m.

F unit. The F unit is the major salt-bearing unit in most parts of the Appalachian basin, where it consists of a series of pure and impure salt beds alternating with shale, dolomite, and anhydrite (fig. 21) and represents the youngest (shallowest) of the salts in this province. The total thickness of the salt-bearing F unit ranges from 60 m near the edges of the basin to more than 300 m in the deep part of the basin (Rickard, 1969).

Individual salts in the F unit are commonly 3 to 25 m thick in Ohio and 20 to more than 50 m thick in parts of south-central New York. In a large part of both these areas the depth to the top of the F salts is 300 to 900 m (fig. 18).

The aggregate thickness of salts in the F unit is commonly 30 to 60 m in Ohio. Here, they make up most of the salts in that state, except where the B salts are thick in Lake and Ashtabula Counties. The aggregate thickness of the F salts is greatest in south-central New York and adjacent parts of Pennsylvania, where more than 150 m of thickness is attained throughout a fairly large area. The salts collectively are at least 30 m thick and are present less than 900 m below the land surface in parts of Steuben, Schuyler, Yates,

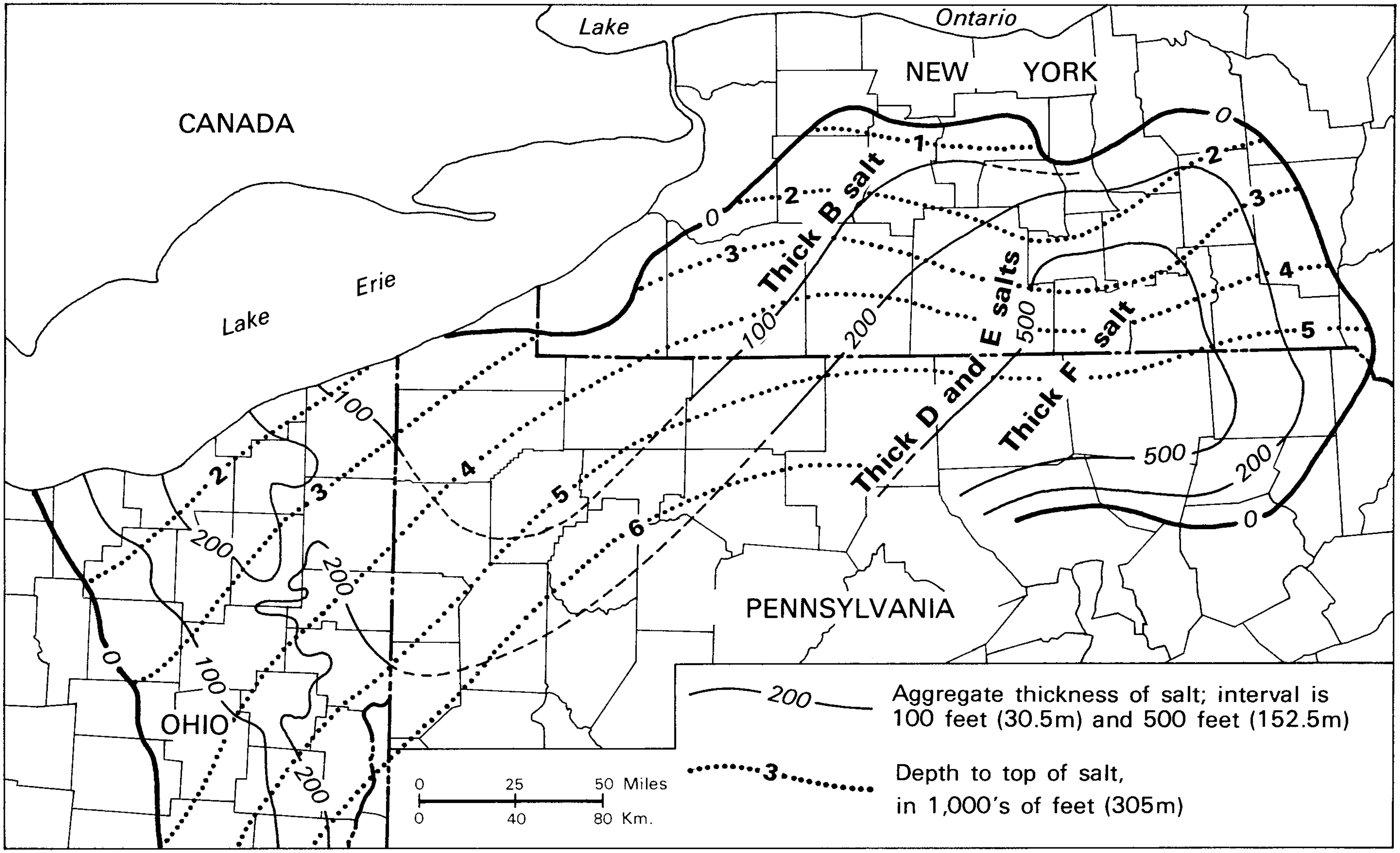


Figure 18. Map showing aggregate thickness in feet and depth below land surface to top of salt beds of Salina Group in Appalachian basin. Modified from Rickard (1969) and Clifford (1973).

Tompkins, Cortland, Cayuga, Seneca, Chemung, and Tioga Counties, New York. The great thickness of salt beds in this area of New York is due in part to deformation and flowage of salt (Jacoby, 1963; Prucha, 1968; Chute, 1972; Frey, 1973; Jacoby and Dellwig, 1974). Additional studies of the thickening and thinning of these salts and their associated structural features are needed in order to evaluate the potential of the F salts.

Salt Dissolution

Data are not readily available to determine the extent of natural dissolution of the Salina salts in the subsurface of the Appalachian basin. Rock units equivalent to the Salina salts crop out in an east-west band across central and western New York. Salt is absent at the outcrop and at shallow depths just south of the outcrop, and the northern edge of the salt (fig. 18) is probably a depositional limit in some areas and a dissolution limit in other areas. No mention of dissolution is made in recent reports, but Lefond (1969) referred to existing salt springs in the Syracuse, New York, area.

Examination of data presented in several plates (5, 7, 8) by Rickard (1969) suggests that dissolution of salt may have occurred in the following areas of New York: in northern Livingston County and nearby areas, where the B salts are 200 to 300 m deep; in central Seneca and Cayuga Counties and nearby areas, where the D salts are 300 to 500 m deep and the F salts are 400 to 600 m deep. Additional study is needed in these areas to establish the possibility and extent of dissolution.

Hydrology

Surface Water

Surface drainage flows northward a short distance into Lakes Erie and Ontario, and it flows southward a great distance to the Gulf of Mexico and the Atlantic Ocean. In northeastern Ohio and northwestern Pennsylvania, the watershed for Lake Erie extends only about 30 to 50 km from the shore. South of this area, tributaries to the Allegheny and Ohio Rivers carry surface water to the Mississippi River and thence to the Gulf.

In New York, major drainageways include the Oswego, Seneca, and Genesee Rivers, draining northward into Lake Ontario, and the Mohawk River and tributaries to the Susquehanna River draining east and south to the Atlantic Ocean. In addition, the Finger Lakes are scattered through an area about 80 by 150 km in the northern part of the area underlain by salt.

Nearly all surface drainage results from precipitation and runoff, but some is derived from springs emerging from glacial drift as well as bedrock. Annual precipitation averages 81 to 102 cm in most parts of the region.

Municipal and industrial use of water from the Great Lakes is large, and inland from the Great Lakes the many other lakes and rivers supply virtually all the fresh water needed for municipal, industrial, and rural use.

Ground Water

The relatively small amount of ground water used in the region comes from both glacial-drift and bedrock aquifers. Where the drift is thick and consists largely of sand, recharge by precipitation is easily accomplished, and water wells provide good yields.

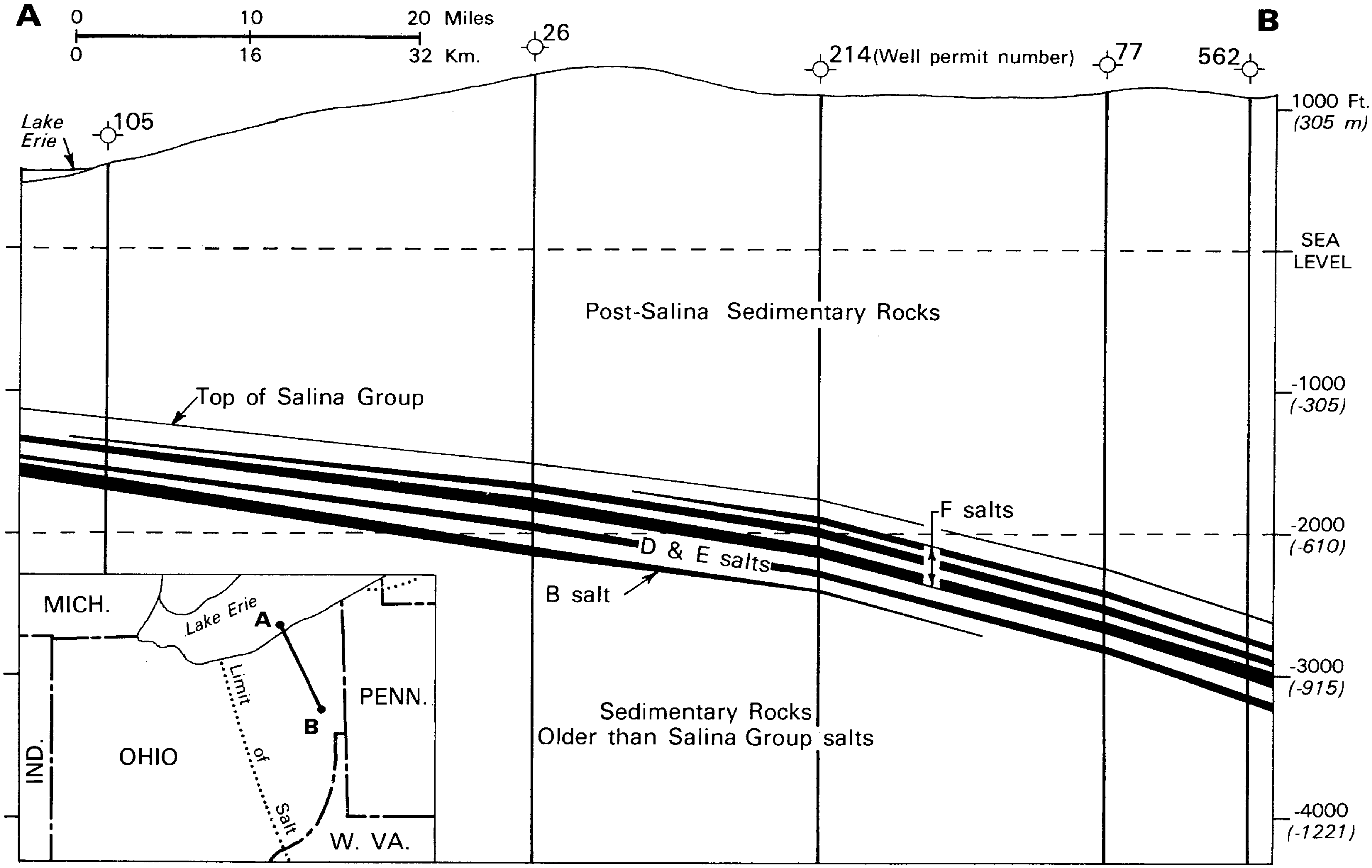


Figure 19. Generalized north-south cross section in northeastern Ohio showing principal salt units of Salina Group. Data from Clifford (1973).

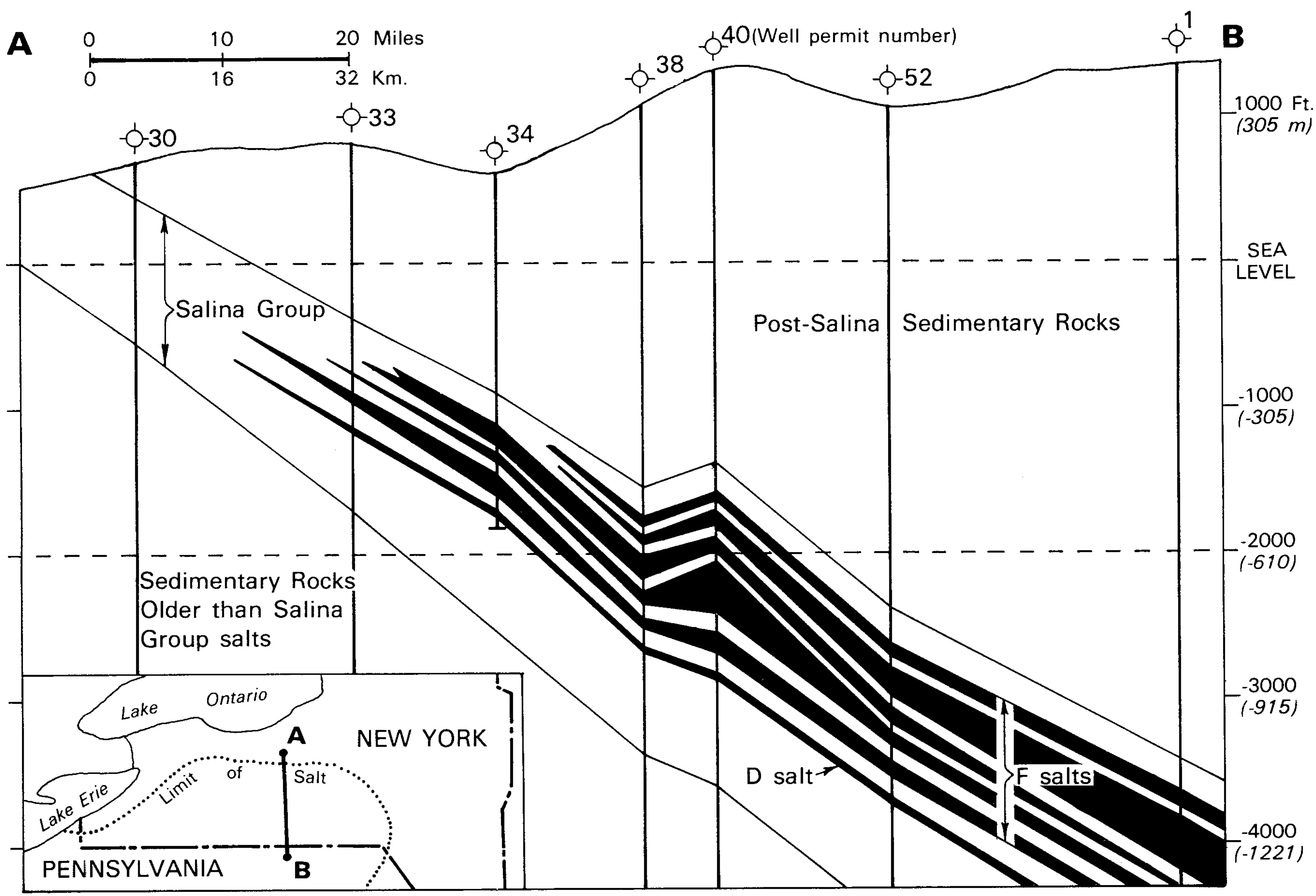


Figure 20. Generalized north-south cross section in south-central New York showing principal salts of Salina Group. Modified from Rickard (1969, pl. 13).

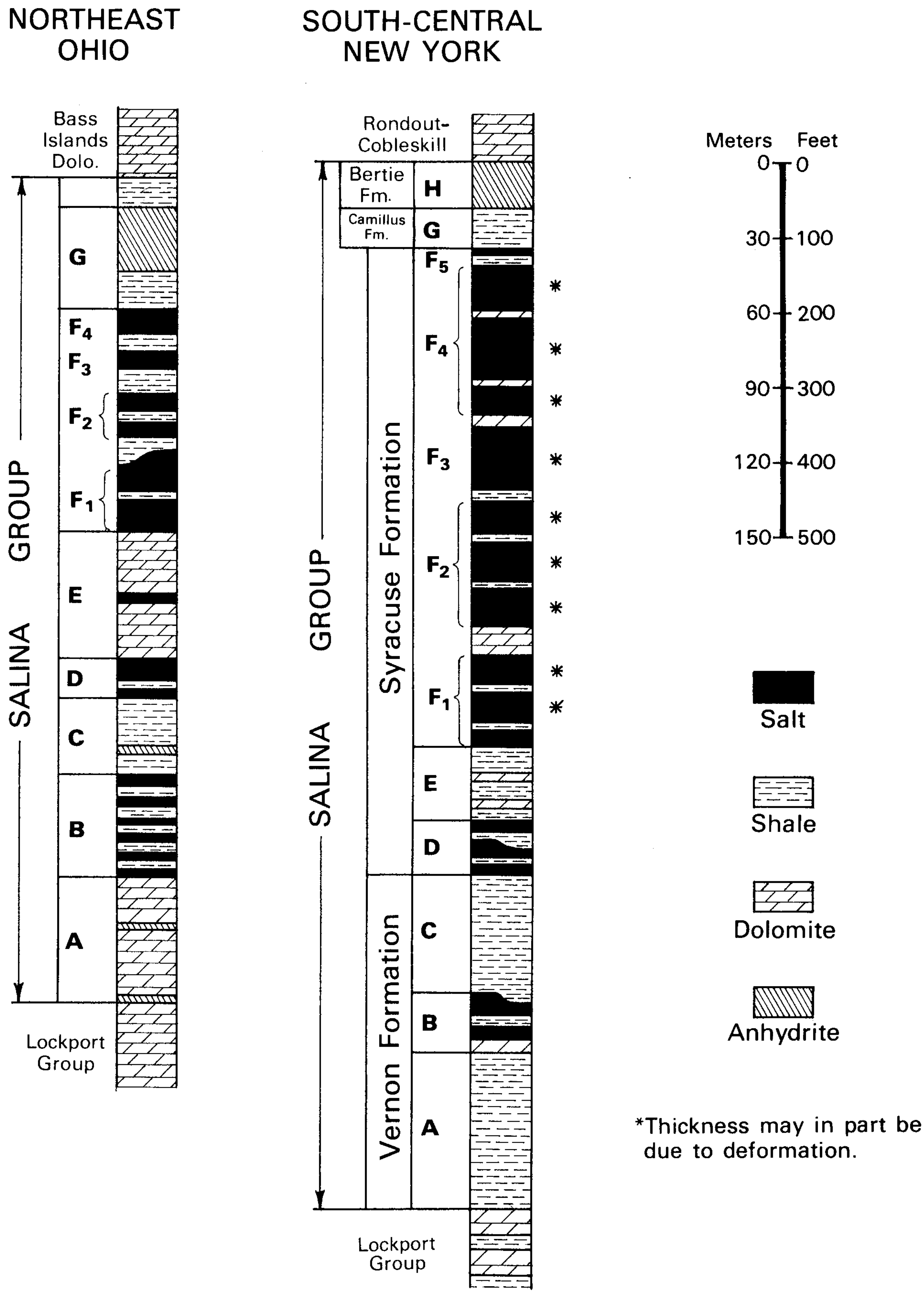


Figure 21. Generalized columnar sections of Salina Group in northeastern Ohio (Clifford, 1973) and south-central New York (Rickard, 1969).

Where the drift is thin and mostly clay, wells produce little or no water. Yields from drift in northeastern Ohio are commonly less than 90 lpm (liters per minute), while those in western and central New York are mostly less than 35 lpm, except along modern or ancient rivers, where some sands yield as much as 375 lpm or more.

The following sandstones are the principal bedrock aquifers in northeastern Ohio and northwestern Pennsylvania: (1) the Allegheny Formation of Pennsylvanian age, which yields enough water only for rural domestic needs; (2) the Pottsville Formation, also Pennsylvanian, the most productive; (3) the Sharpsville Sandstone Member of the Cuyahoga Formation of Mississippian age; and (4) locally only, the topmost part of the Berea Sandstone (Piper, 1972). Ground-water use is small, and the water ranges from soft to hard and from an acceptable to an unacceptable level of dissolved solids.

In western and central New York, the major bedrock aquifers are limestones and dolomites of Silurian age, including the Salina and Lockport Groups. In the vicinity of Rochester, the Salina yields less than 100 lpm of hard water with a high sulfate content, and the Lockport yields an average of 350 lpm and a maximum of 1,875 lpm of water with large amounts of sulfate and chloride (Piper, 1972).

In most areas, fresh-water aquifers in the Appalachian basin are shallow and are considerably above the underlying thick salts. Where Silurian limestones and dolomites are the principal aquifers, salts of equivalent age either were dissolved from those areas at some time in the geologic past or were not deposited in the first place. Thus the ground-water resources of the basin are not closely associated with the thick salts that might be used for waste storage.

Seismic Activity

The number of recorded earthquakes in the northern part of the Appalachian basin is small, compared to most other parts of the United States (fig. 15). Quakes with a Modified Mercalli Intensity of V (MM V) or greater are sparse in the region, except in the Attica area of western New York and the Cleveland area of northeastern Ohio (Coffman and von Hake, 1973). Other studies of seismic activity include those of Smith (1966) and Hadley and Devine (1974). Most of the northern Appalachian basin is within zone 1 (expected minor damage) on the seismic-risk map prepared by S. T. Algermissen (ESSA/Coast and Geodetic Survey, 1969) (fig. 16), although the northernmost area underlain by Salina salt is within zone 2 (expected moderate damage), and the Attica area, which is north of the Salina salt, is within zone 3 (expected major damage).

Seven earthquakes of MM V or greater have been recorded in areas underlain by salt in the northern Appalachian basin. Six of these events occurred in Ohio: 1 near Lorain in 1928 (MM V), 1 in the Lake Erie area in 1943 (MM IV-V), and 4 of MM V in the Cleveland area in 1906, 1955 (2), and 1958. The seventh earthquake occurred near Erie, Pennsylvania, in 1934 (MM V).

Near Attica, at the northwest edge of salts in Wyoming and Genesee Counties, 5 earthquakes were recorded: 1 event of MM VIII in 1929, 2 events of MM VI in 1966 and 1967, and 2 events of MM V in 1929 and 1955. Within 100 km northwest of Attica, 4 other earthquakes of MM V and MM VI occurred, in 1857, 1873, 1879, and 1962.

Therefore, the earthquake activity and seismic risk are low in most of the area underlain by thick salt deposits at moderate depth. Moderate levels of seismicity have been recorded in the Cleveland area, and still higher levels were observed just north of the salt area near Attica.

Mineral Resources

Oil and Gas

Oil and gas production in the northern part of the Appalachian basin is from Cambro-Ordovician, Silurian, Devonian, Mississippian, and Pennsylvanian sedimentary rocks (Woodward, 1958; Netherland, Sewell and Associates, 1975b). The large productive area in the center or deeper part of the basin represents mainly the relatively shallow Pennsylvanian, Mississippian, and Devonian fields that are above the Late Silurian Salina salts (fig. 22). A band of production along the western and northern margins of the basin represents, for the most part, Cambro-Ordovician and Silurian fields that are beneath the Salina Group.

Pre-Salina reservoir rocks are limestones, dolomites, and sandstones that produce chiefly from stratigraphic traps. Shallow- and medium-depth production from these units along the western and northern edges of the basin has been established for many years, and the rocks still yield minor discoveries from time to time. Drilling for these units in deeper parts of the basin is sparse and has been nonproductive, but it is sufficient to indicate that reserves commensurate with the expense of such efforts are difficult to find (Netherland, Sewell and Associates, 1975b). Preliminary study by Netherland, Sewell and Associates (1975b) indicates that the density of wells drilled into or through the Salina salts southeast of the main area of pre-Salina production is less than 1 well per 250 sq. km.

In the central portion of the Appalachian basin, thousands of shallow wells have been drilled to produce from Devonian, Mississippian, and Pennsylvanian sandstone reservoirs found above the Salina salts. Many of these wells were drilled in the late 1800's and early 1900's and because of depletion of the fields are now abandoned. Current exploration of these units centers chiefly on development of known reservoirs. An exception is drilling for reefs in the Devonian Onondaga Limestone, in which several fields have produced gas in Steuben County, south-central New York.

Based upon their preliminary study, Netherland, Sewell and Associates (1975b) concluded that there are certain areas in easternmost Ohio, western Pennsylvania, and south-central and southwestern New York where present and/or future economic oil and gas production from pre-Salina rocks will not occur.

Salt

The great salt resources of Ohio, Pennsylvania, and New York are limited to the Salina Group of Silurian age. Salt or salt brines are produced from the Salina in mines or brine wells at 11 localities in Ohio and New York (fig. 6), but none is being produced in Pennsylvania (U.S. Bureau of Mines, 1972). In Ohio, salt is being mined underground in Lake and Cuyahoga Counties, and numerous brine wells have been completed in Silurian strata in Lake, Summit (two plants), and Wayne Counties. In New York, salt mines are located in Tompkins and Livingston Counties (the Retsof mine in Livingston County is the largest underground salt mine in the world), and three brine-well systems are operating in Schuyler, Onondaga, and Wyoming Counties.

With the widespread distribution of thick salt beds in the Appalachian basin, there are many areas where a waste repository could be built that would be remote from mines or brine wells, and from salt resources that might be needed in the future.

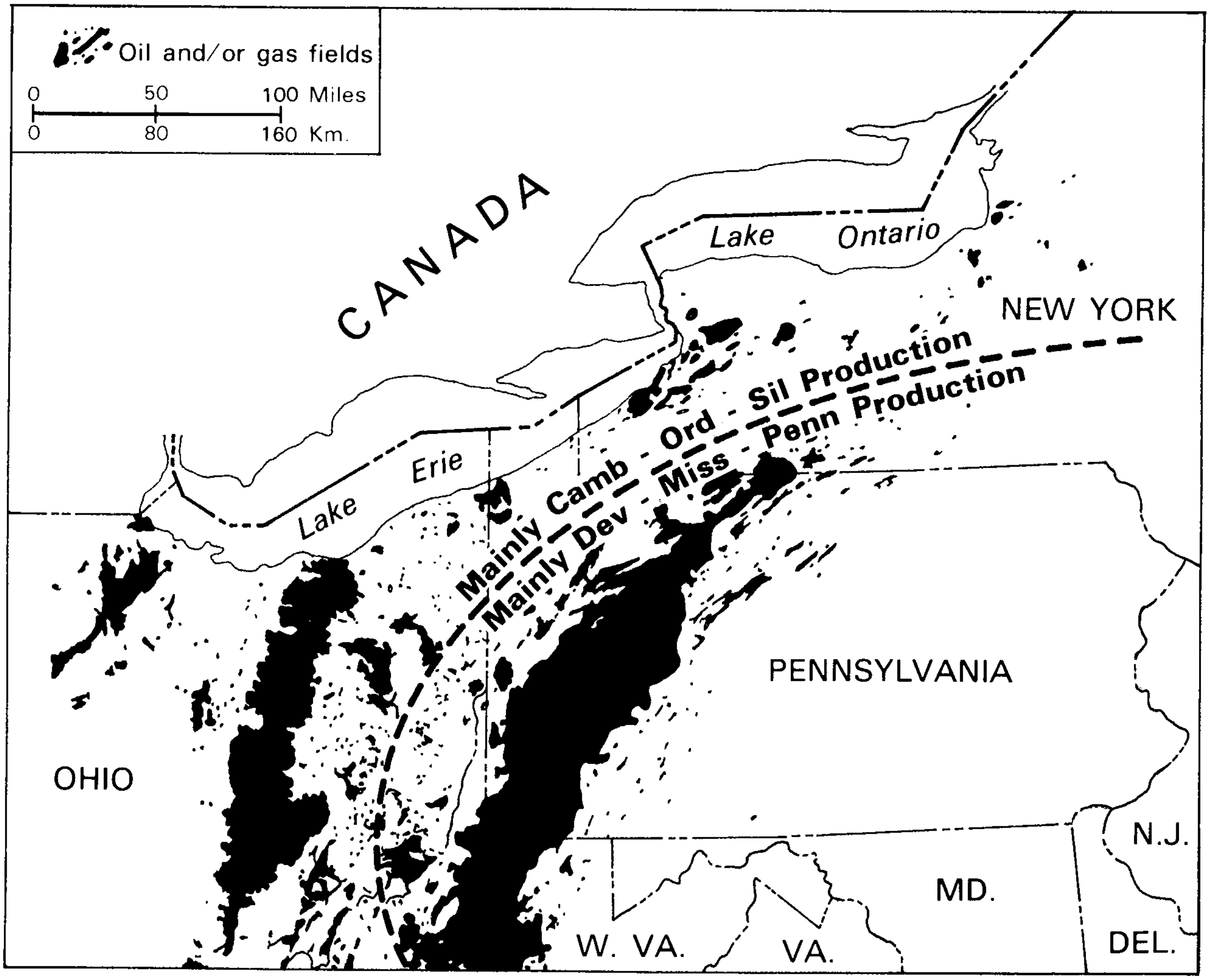


Figure 22. Map of oil and gas fields in northern part of Appalachian basin showing areas where production is mainly from strata either below or above Late Silurian Salina Group salts (modified from Netherland, Sewell and Associates, 1975b).

Other Minerals

Gypsum in the Salina Group is being mined underground at three sites in Erie and Genesee Counties, New York. The two gypsum mines in Ohio are in Ottawa County, outside the area underlain by salt.

Bituminous coal of Pennsylvanian age is being strip mined in parts of eastern Ohio and western Pennsylvania. In Ohio, the mining extends as far north as parts of Wayne, Stark, and Mahoning Counties, whereas in Pennsylvania it extends into most of the western counties.

Stone production from exposed limestone, dolomite, and sandstone bedrock is currently active at many places in Ohio, Pennsylvania, and New York. Limestone and dolomite are used for aggregate, lime, cement, and for chemical and agricultural uses. Sandstone, principally the Sharon Conglomerate in Ohio, is used as crushed stone, glass and foundry sand, and/or dimension stone.

Clays and shales from bedrock or glacial drift are mined at the surface at many places in the area underlain by salt. The material is used primarily in making brick, tile, and other common clay products, but some also qualifies as refractory clay.

Sand and gravel are the most widespread mineral deposits being mined in the 3-state area. Commercial deposits have been developed in glacial drift deposits, such as outwash deposits, kames, eskers, and glacial lake-shore sediments, and also in river terraces and alluvium. Hundreds of companies operate open pits in the area underlain by the Salina salts, and most of these sites are located near the expanding urban areas.

Therefore, other known minerals in the area underlain by salt either are not commercially recoverable or they are being developed in surface mines that would not conflict with waste storage except in the immediate vicinity of the site's surface facilities.

Regional Evaluation for Storage of Radioactive Waste

Data reviewed here indicate that thick deposits of rock salt are present at moderate depths in three principal areas of the Appalachian basin: northeastern Ohio, southwestern New York, and south-central New York. Salt beds have not been dissolved or structurally deformed and fractured in northeastern Ohio or southwestern New York. In south-central New York, however, there is evidence of salt dissolution in the northern part of the area, and deformation and flowage of salt have occurred in the south. Except for post-Silurian décollements and salt flowage in parts of south-central New York, these three areas have been tectonically stable since deposition of the salt. Seismic activity and seismic risk are low in the region, except in the Cleveland area and near Attica (which lies outside of the salt area).

The northeastern Ohio area is underlain by an aggregate salt thickness of 30 m to more than 60 m at a depth of less than 900 m (fig. 18). Within this area the total thickness of salt-bearing strata ranges from 60 to 150 m. Among the geologic and other factors that need to be more fully studied are current land use and mineral-resource development. The area contains a mixture of urban, suburban, and rural lands, and the Ravenna Arsenal is also present in northeastern Portage County. Mineral development includes the production of oil and gas from pre-Salina strata at a number of sites in the area as well as salt mines and brine-well plants at several localities. There are, however, some moderately large tracts within this area that are free of boreholes or mines that penetrate the salts.

In southwestern New York, the B unit has an aggregate salt thickness of 15 to 30 m, and locally the highest bed of the B unit is 5 to 6 m thick. Also in this same area, the overlying D and F salts appear to have an aggregate thickness of 10 to 30 m, thus increasing the total aggregate thickness of salt to perhaps 40 to 60 m locally.

In south-central New York, the Salina F salts aggregate 30 m to more than 150 m thick at a depth of less than 900 m (fig. 18). This area must be studied further to determine if salt dissolution has occurred in the north and also the extent of deformation and salt flowage in the south.

In both areas of New York, the several oil and gas fields produce from rocks overlying the salt deposits, and few boreholes have been drilled into or through the salts. Salt is recovered by underground mines or brine wells at several localities in New York. Most of the land in the New York areas is rural, although the Finger Lakes are important recreational sites and there are several large cities in and near the areas.

GULF COAST BASIN

Structure and Geologic Framework

The Gulf Coast basin or geosyncline is that more localized, northern portion of the Gulf of Mexico basin. It extends westward from Alabama through Mississippi and Louisiana into southern Arkansas and Texas, and southward into the offshore. This significant regional feature appears to have originated in the early Mesozoic, but it did not reach its maximum development, as measured by pronounced subsidence and sediment infilling, until the Cenozoic. The stratigraphic section ranges in thickness from about 1,000 m along the northern boundary in southern Arkansas to possibly as much as 18,000 m in south Louisiana and the near offshore. Since the mid-Mesozoic, the depositional axis of this geosynclinal basin has shifted progressively southward toward the present-day Gulf of Mexico; as well, the center of maximum deposition shifted eastward into southeast Louisiana by mid-Cenozoic time (Lafayette and New Orleans Geological Societies, 1968). The greatest sedimentation took place during the Tertiary and was dominated by clastic deposits in which facies changes on a regional basis are important in this major petroleum-producing province. Prograding depositional systems, fluctuating water depths, and localized sedimentation rates dictated by faults characterized formation of the Cenozoic sequence.

The regional strike of the various subcrop belts essentially parallels the coastline. Cretaceous strata in the north give way to successively younger Cenozoic (Eocene to Plio-Pleistocene) intervals in a gulfward direction. Although the regional dip is also gulfward, faults and other structures create localized areas of dip reversal. In the subsurface, facies changes, both those aligned in the direction of progradation and others along strike, together with regional and local faulting, and numerous salt-related structures, complicate the geology appreciably.

Quaternary and early Holocene deposits of the Gulf Coast basin correspond to stream-deltaic sedimentation related to glacial events, especially changes in sea level. Terrace deposits—named the Williana, Bentley, Montgomery, Prairie, Late Wisconsin, and Deweyville, from oldest to youngest (Kolb, *in* Martinez and others, 1975)—were formed during interglacial stages and then were partially eroded and dissected as downcutting increased in response to falling sea level during glacial stages. Remnants of these terraces and other alluvium are exposed along present-day stream valleys or within the central depressions above certain salt domes. These same sediments are, however, warped upward above other domes, especially several nearer to the modern coastline. Quaternary and Holocene alluvial, deltaic, and swamp deposits have also been formed behind barrier-bar systems that roughly parallel the shoreline.

For more comprehensive treatment of the geology of the Gulf Coast basin, references by Murray (1961) and the Lafayette and New Orleans Geological Societies (1968) provide both detailed discussion and extensive bibliographic citations. The comprehensive bibliography compiled by Braunstein (1970) also contains many useful references.

The Gulf Coast basin is one of the most significant salt-dome provinces in the world (Halbouty, 1967; Lefond, 1969). As depicted in figure 23, more than 260 domes are either known or inferred from the onshore portion of this region alone. Elsewhere throughout the Gulf of Mexico region, additional salt domes have been reported from Cuba, the Veracruz-Tabasco section of Mexico, and the Sigsbee Deep within the central Gulf (Murray, 1968). Salt-supported structures, mainly anticlinal, are also present in southern Arkansas (Bornhauser, 1958) and in several provinces of both northeastern and southeasternmost Mexico (Murray, 1968).

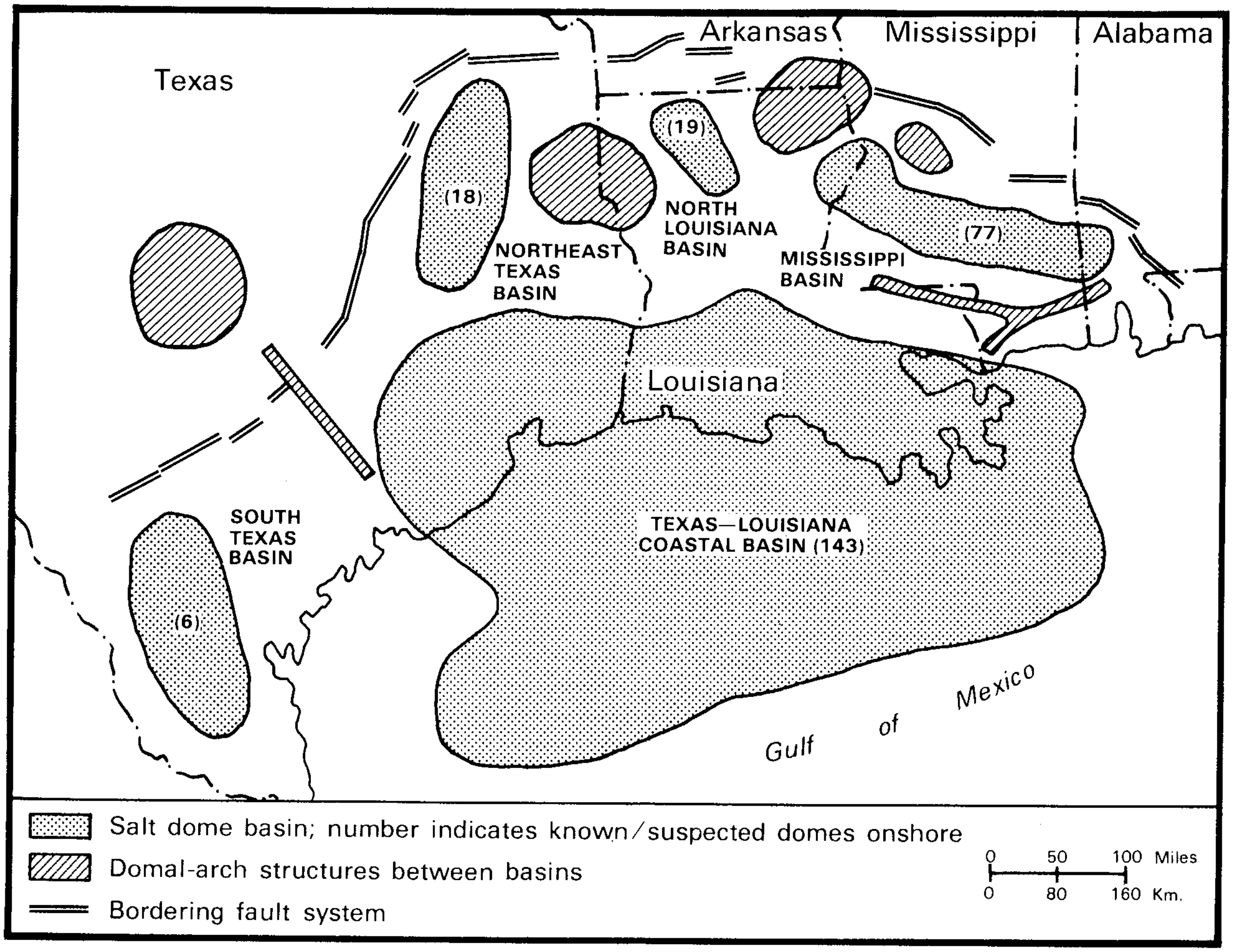


Figure 23. Map showing five salt-dome basins and other principal regional structural features in Gulf Coast region (after Murray, 1961, 1968; Anderson and others, 1973).

Gulf Coast salt domes, because of several unique characteristics and economically important associations of petroleum, native sulfur, and salt, have been the target of intensive geologic and geophysical investigations. Spooner (1926), DeGolyer (1926), Atwater and Forman (1959), Durham (1960), Hawkins and Jirik (1966), Halbouty (1967), and the Louisiana Department of Conservation (1975) are noteworthy among authors who have treated domes from a regional perspective. Additional references, many about specific domes, individual dome-related features, and petroleum fields associated with domes, can be found in the extensive bibliography compiled by Braunstein and O'Brien (1968). Gulf Coast domes were discussed briefly by Pierce and Rich (1962), whereas articles by Anderson and others (1973), Ledbetter and others (1975), Martinez and others (1975, 1976), and Netherland, Sewell and Associates, Inc. (1976a, 1976b) have focused more specifically on the potential utility of salt domes for the geologic storage of high-level radioactive wastes.

Salt Deposition and Origin of Salt Domes

Brief commentary about the complex stratigraphic and tectonic history of the Gulf of Mexico is necessary against which to consider conflicting hypotheses about the origin and geologic age of the parent salt, known as the Louann Salt, and the mode of diapiric salt intrusion. In order ultimately to form the several hundred domes identified to date within this region, a thick and regionally extensive sequence of rock salt must have been initially deposited within a major depositional basin. Information from deep drilling and adjacent regional trends has led to the belief that the Gulf Coast basin developed amid a Paleozoic "basement" that varied from one area to another in specific geologic age, lithologic expression, and degree of prior deformation. Except for along the eastern margin, the basin was surrounded by preexisting orogenic belts such as the Appalachian and Ouachita trends. The northern margin of the basin, from Alabama to the Texas-Mexico border, is marked by a series of bordering fault systems, known successively as the Gilbertown-Pickens, South Arkansas, Balcones, Talco, Mexia, and Luling zones.

According to Kupfer (1974), one accepted view is that deposition of the Louann Salt began first in the northern region, as delineated by these fault systems, and progressed southward. Even if evaporite sedimentation had expanded in this manner, the basin, as it underwent continued subsidence, received sufficient clastic materials so that various nonsalt sequences underlie, intergrade with, and overlie this principal evaporite formation. These nonsalt units include certain red beds whose geologic age and correlative relationships are not known with absolute certainty. Under this designation are the Eagle Mills, Morehouse, Werner, and Norphlet Formations (fig. 24).

An older view concerning the origin of the Gulf Coast basin holds that the basin began sinking along the several zones of peripheral faulting that were related to post-Appalachian orogenic adjustment. Under this explanation, evaporites, mainly salt of either Permian or Jurassic age, were formed owing to restriction of marine circulation across a narrow, barred channel, which was postulated to lie along the western margin of the basin (Halbouty, 1967; Murray, 1968). A more recent concept contends that the basin evolved as the result of early Mesozoic rifting and the northwestward migration of the North American continental plate away from Africa and South America (Dietz, 1973; Kupfer, 1974). Restricted marine circulation has been ascribed also to a trench-like connection to the then-existent Pacific Ocean, although there is evidence that, prior to plate-tectonic rifting, a proto Gulf of Mexico already existed (Kupfer, 1974).

<table>
<tr><th>SYSTEM</th><th>SERIES</th><th>GROUP</th><th>FORMATION</th></tr>
<tr><td rowspan="7">JURASSIC</td><td rowspan="5">LATE</td><td rowspan="2">COTTON VALLEY</td><td>Schuler</td></tr>
<tr><td>Bossier</td></tr>
<tr><td rowspan="3">LOUARK</td><td>Haynesville-Buckner</td></tr>
<tr><td>Smackover Limestone</td></tr>
<tr><td>Norphlet</td></tr>
<tr><td rowspan="2">EARLY-MIDDLE</td><td rowspan="2"></td><td>Louann Salt</td></tr>
<tr><td>Werner Anhydrite</td></tr>
<tr><td>TRIASSIC</td><td>LATE</td><td>? ? ?</td><td>Eagle Mills</td></tr>
<tr><td>PENNSYLVANIAN</td><td>LATE</td><td>? ? ?</td><td>Morehouse</td></tr>
</table>

Figure 24. Generalized stratigraphic succession of Jurassic and older rocks applicable to Gulf Coast basin and its several salt-dome basins (after Lafayette and New Orleans Geological Societies, 1968; Anderson and others, 1973).

The earlier concept holds that formation of the Louann Salt ceased when restricted marine conditions diminished in response to the continued development of the basin coupled with enlarged carbonate sedimentation along expanding shelf areas subjected to more normal marine circulation. According to the plate-tectonic concept, salt deposition was halted, except for several isolated, smaller basins in the southern Caribbean region, because plate spreading surpassed the rate of evaporitic deposition. This in turn enabled open marine circulation to be established between the Gulf of Mexico and an emerging Atlantic Ocean.

Debate also has existed in regard to the exact geologic age of the salt from which Gulf Coast salt domes arose. As summarized by Halbouty (1967), several workers, most notably Hazzard and others (1947), previously believed that the Louann Salt was spatially related to the evaporites found in the Delaware basin of west Texas and New Mexico and hence was Late Permian in age. Although that association was tempting, equivalency with the Castile salt is no longer accepted by Gulf Coast geologists. Rather, the more widely held contention is that the Louann Salt is probably no older that Early Jurassic, although a Late Triassic age has been suggested by some. Salt formation in Jurassic time more closely agrees with the timing for either of the tectonic mechanisms alternatively invoked to explain the origin of the basin. Palynological work by Jux (1961), although not unequivocal and thus open to some debate, and work by Kirkland and Gerhard (1971) support the assignment of a Jurassic age to the Louann Salt.

A related question is whether all the salt domes in the Gulf Coast basin originated from the Jurassic Louann Salt or its equivalents. On this point, too, there exists some conflicting information. Meyerhoff and Hatten (1968) indicated that the salt within several diapirs in Cuba was also Jurassic. In contrast, Viniegra (1971) showed that the age of the salt in eastern Mexico varies so that some sequences are as young as Cretaceous; other salt units as young as Miocene have also been reported from southeastern Mexico (Wilson, 1977). Wilson (1975) even suggested that some of the salt involved in Gulf Coast salt tectonics may be Oligocene to Miocene in age. Kupfer (1977) agreed that non-Louann salts may be present but disagreed with Wilson's contention that this hypothesis was applicable to the so-called "Five Island" domes in south Louisiana. Tertiary-age evaporites in the Gulf Coast cannot be ruled out, but most investigators still contend that the Louann Salt, although it could range from Late Triassic to Late Jurassic in age, served as the principal source of salt for the region's numerous diapirs.

The exact origin of salt diapirs in general or Gulf Coast salt domes in specific, despite much study and speculation and numerous hypotheses, is not fully understood. Nevertheless, the prevailing view about Gulf Coast domes relates to flowage and upward movement of plastically deformed salt in response to overburden pressure from the overlying sediments. According to this concept, a thick layer or layers of bedded salt, typically referred to as the "mother salt," flowed into structures that either rose through or pierced the overlying sediments in response to the resulting gravitational inequilibrium or else remained static while additional sediments "downbuilt" around them. Although the thickness of the original source salt bed has never been established because of no complete penetration by wells, it has been estimated to range from 450 m in north Louisiana (Andrews, 1960) to more than 1,500 m (Halbouty and Hardin, 1956). Parker and McDowell (1955) felt that the latter thickness was a minimum value based on experimental calculations. Commentary by Martinez and others (1975) indicated that the original salt sequence averaged between 600 and 900 m over the region characterized by domes. Depending upon geographic location, the depth to the "mother salt" varies from as shallow as 1,500 m in southern Arkansas–north Louisiana to a postulated depth of 12,000 to 18,000 m along coastal Louisiana.

Figure 25 illustrates schematically how salt domes, forming initially near the northern extent of the salt and progressively developing southward through geologic time, arose in response to increasingly greater burial by successively younger sediments. As shown, the great influx of Tertiary clastics clearly made a significant impact on the generation of salt domes within the Texas-Louisiana coastal basin. Missing from that diagram, however, is an indication of what mechanism, outside of confining pressure, initiated the upward rise of salt. As summarized by Murray (1968), variations in overburden thickness and regional faulting appear the most promising causes. A regional alignment of salt ridges and the clustering of major salt domes suggest linear fault control. Areas of thicker sedimentary sequences, known as depocenters, also show a close association with major regional growth faults. These faults demonstrate simultaneous fault movement and sedimentation so that the downthrown sides contain expanded stratigraphic intervals. Many Gulf Coast geologists have contended that growth faults intersect deeply buried, salt-supported ridges, where salt flowage was either initiated or more pronounced (Lafayette and New Orleans Geological Societies, 1968).

The Gulf Coast basin or geosyncline, as shown previously in figure 23, actually consists of several smaller basins separated by various positive structural features such as the San Marcos arch, Sabine uplift, Wiggins arch, and Monroe uplift. In terms of salt-dome occurrences, the principal salt-dome basins include the (1) South Texas, (2) Northeast Texas, (3) North Louisiana, (4) Mississippi, and (5) Texas–Louisiana coast. The latter contains salt domes in both the onshore and offshore.

In addition to these dome-bearing basins and the intervening interbasinal features, Gulf Coast geology is typified by many, more localized structures. Many are related either to zones of regional salt flowage or to salt domes. Dome-related structures of particular interest include radial, peripheral, and graben fault systems and rim synclines. The latter are those synclinal features depicted by thickening in the overlying stratigraphic sequences around domes, and they represent areas from which the salt migrated into the salt masses.

Rim synclines are important because of the information they provide about the time and amount or rate of salt movement into some diapiric masses. Around those domes where the proximity of other diapirs has not distorted the rim synclines, characteristics of these features include (1) better or larger development along the downdip (with regard to the surrounding strata) flank of the dome, (2) narrower expression in successively younger strata, and (3) migration of the sequence of rim synclines toward the dome in successively younger strata. Analysis of these features by Kupfer (*in* Martinez and others, 1975, 1976) in reference to absolute time of the stratigraphic intervals involved has led to the assignment of growth rates within the North Louisiana basin. The well-developed rim synclines surrounding most domes within the Northeast Texas basin were also utilized in uplift-versus-time studies conducted there by Netherland, Sewell and Associates (1976a).

Previous Studies of Salt Domes Relative to Radioactive-Waste Storage

Although Gulf Coast salt domes were discussed by Pierce and Rich (1962), no effort was made to discriminate between either the several salt-dome basins or individual domes in regard to their general suitability. The great thicknesses and purity of salt

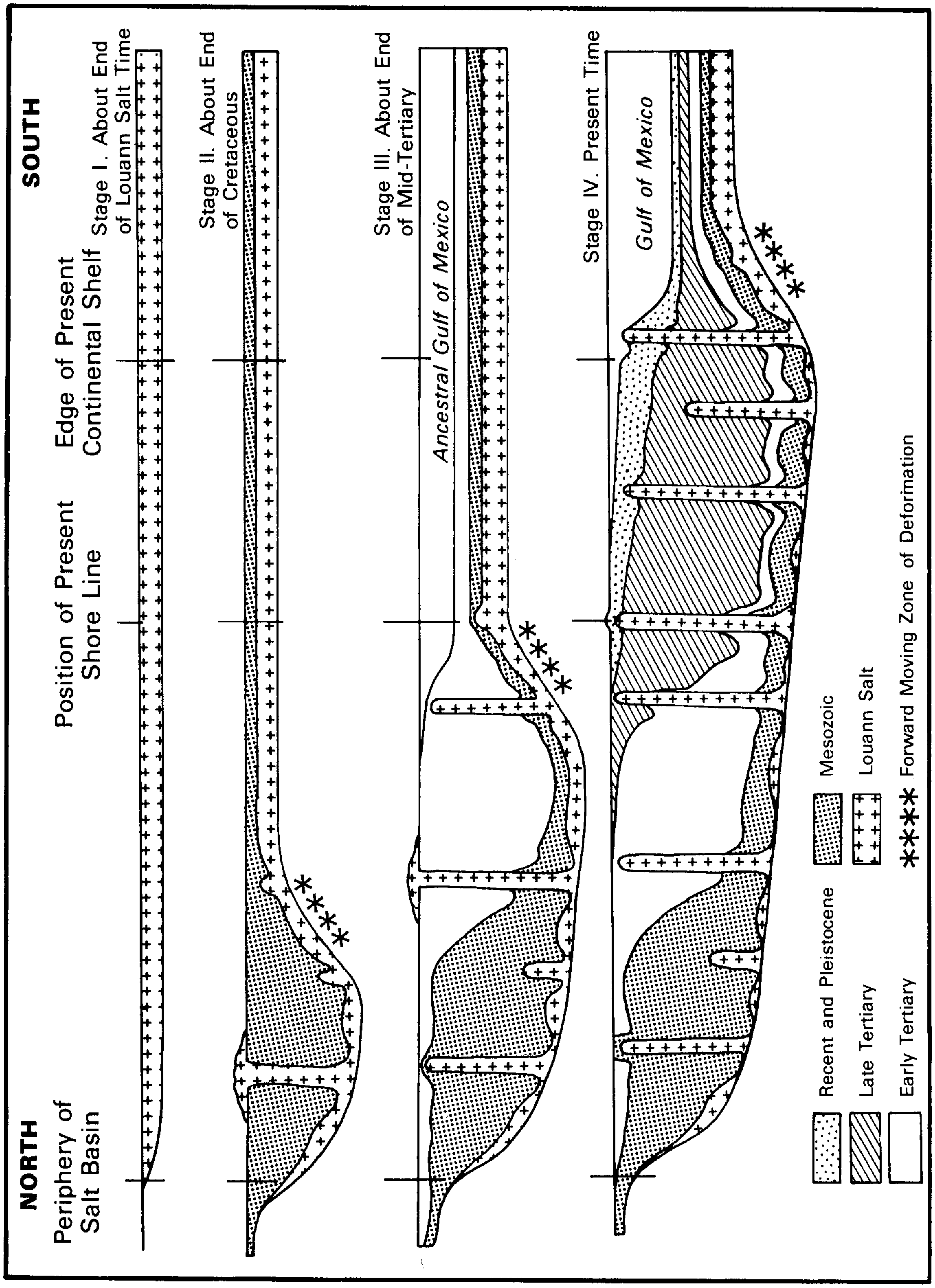


Figure 25. Generation of Gulf Coast salt domes through geologic time (after Hanna, 1959).

domes were cited, however, as favorable factors. Gera (1972) also considered salt domes in his article about salt tectonics but did not specifically evaluate any Gulf Coast domes.

Anderson and others (1973) conducted the first assessment of onshore salt domes with regard to their general potential for additional study. Based upon the subsurface depth to the top of the salt in the domes and the degree of industrial usage, these investigators grouped the 263 known and suspected domes into two general categories. Any dome whose upper salt surface was deeper than 600 m, or for which petroleum production, cavern storage of hydrocarbons, salt or sulfur production, or a combination of these uses indicated appreciable development by industry, was considered less suitable and was not recommended for further study at that time. On these bases, 148 domes were too deep, and 79 exhibited competing uses. The 36 domes that met the general considerations of Anderson and others (1973) are concentrated within the more northern or interior basins (fig. 26). These authors also summarized the geology of the five salt-dome basins and inventoried the available geologic, geophysical, and hydrologic data on the 36 domes that they recommended.

Ledbetter and others (1975) also investigated Gulf Coast domes by means of some generalized approaches that included consideration of topography and surface-drainage features as well as subsurface hydrology. Although much of this work relied upon a review of the existing literature, three noteworthy considerations were that (1) heat from radioactive waste would not be expected to induce renewed tectonic movement in a dome, (2) domes sheathed by shale and below the level of local fresh-water aquifers might exhibit a reduced possibility of salt dissolution, and (3) the large vertical extent of salt domes could prove beneficial in terms of possible repository design. These investigators, like Anderson and others (1973), recommended further that additional data be acquired. Based upon their generalized study, Ledbetter and others (1975) felt that domes within the interior basins offered more potential.

Martinez and others (1975, 1976) extended these earlier studies by investigating 17 domes in the North Louisiana basin and 9 domes in the Northeast Texas basin for which they felt adequate data were available. They specifically studied salt movement through geologic time by analyzing rim-syncline development, the salt volumes involved, and regional stratigraphic relationships. Also studied was hydrologic stability by means of measuring saline-ground-water plumes within fresh-water aquifers adjacent to salt domes and analyzing surface "salines" above certain domes (fig. 27). The potential for surface flooding was also considered. Other investigative approaches have centered upon the (1) extent of past salt dissolution as shown by cap-rock features, especially the cap-rock–salt interface; (2) local and regional hydrology, using well-log analysis on existing borehole data, and several recently drilled exploratory water wells; (3) determination of current tectonic movement or lack thereof through the use of instrumentation arrays, which include tiltmeters, precise-leveling stations, and microseismic monitors; and (4) nature of Quaternary strata above domes to determine whether they have been affected by more recent salt movement. In the latter case, shallow geophysical profiles, borings, and detailed logging have served as the major evaluative techniques.

Several domes within the Northeast Texas basin have also been studied by Netherland, Sewell and Associates (1976a). These workers analyzed the uplift-versus-time growth of these domes and attempted to evaluate hydrologic stability where available well-log data were adequate. Effort was also made in their study to assess the current rate of salt dissolution on certain domes, to integrate existing geophysical data into an understanding of the basin and the salt domes there, and to recommend what additional information should be obtained.

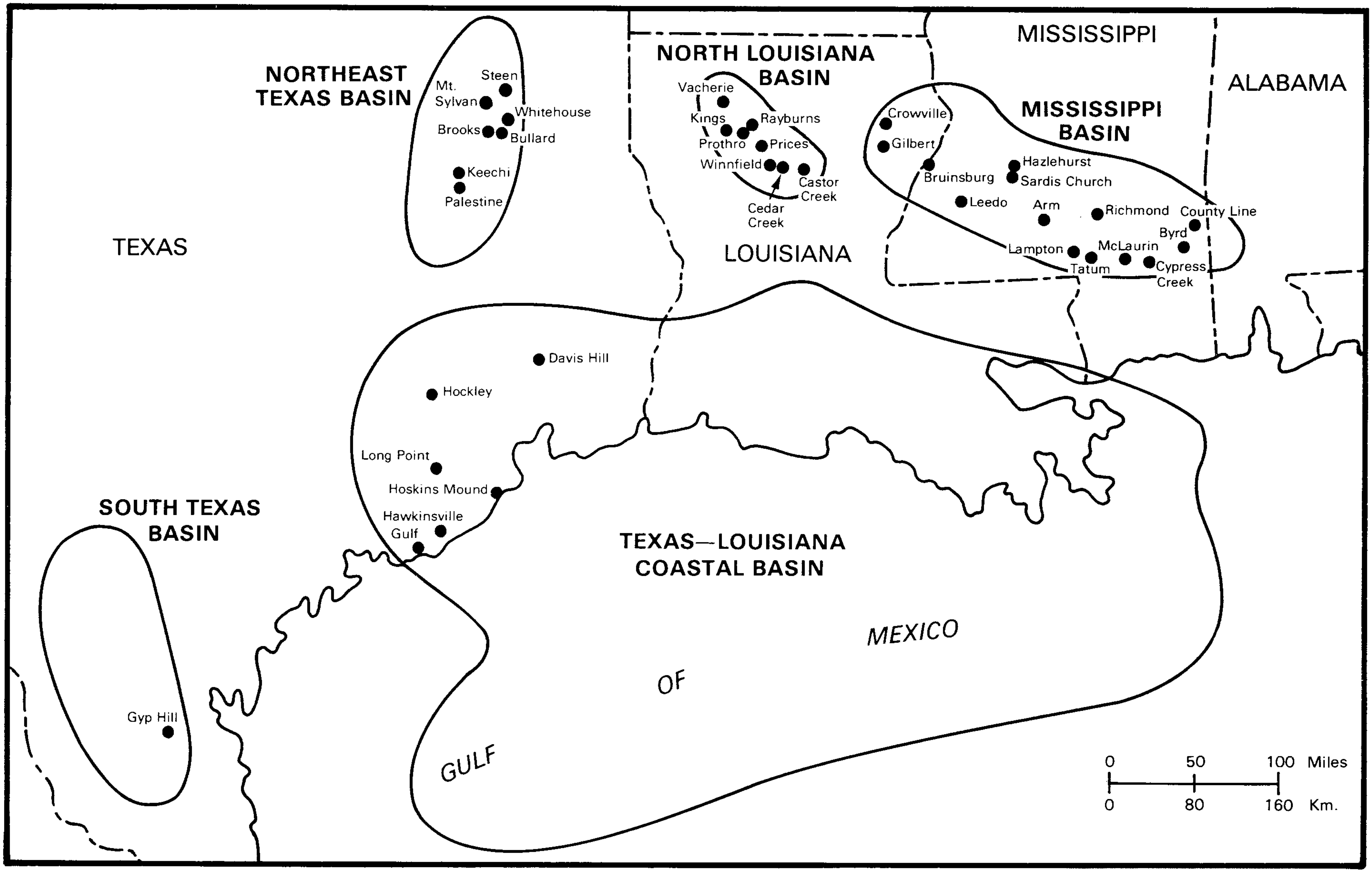


Figure 26. Distribution of Gulf Coast salt domes recommended for further study by U.S. Geological Survey investigation (after Anderson and others, 1973; Ledbetter and others, 1975).

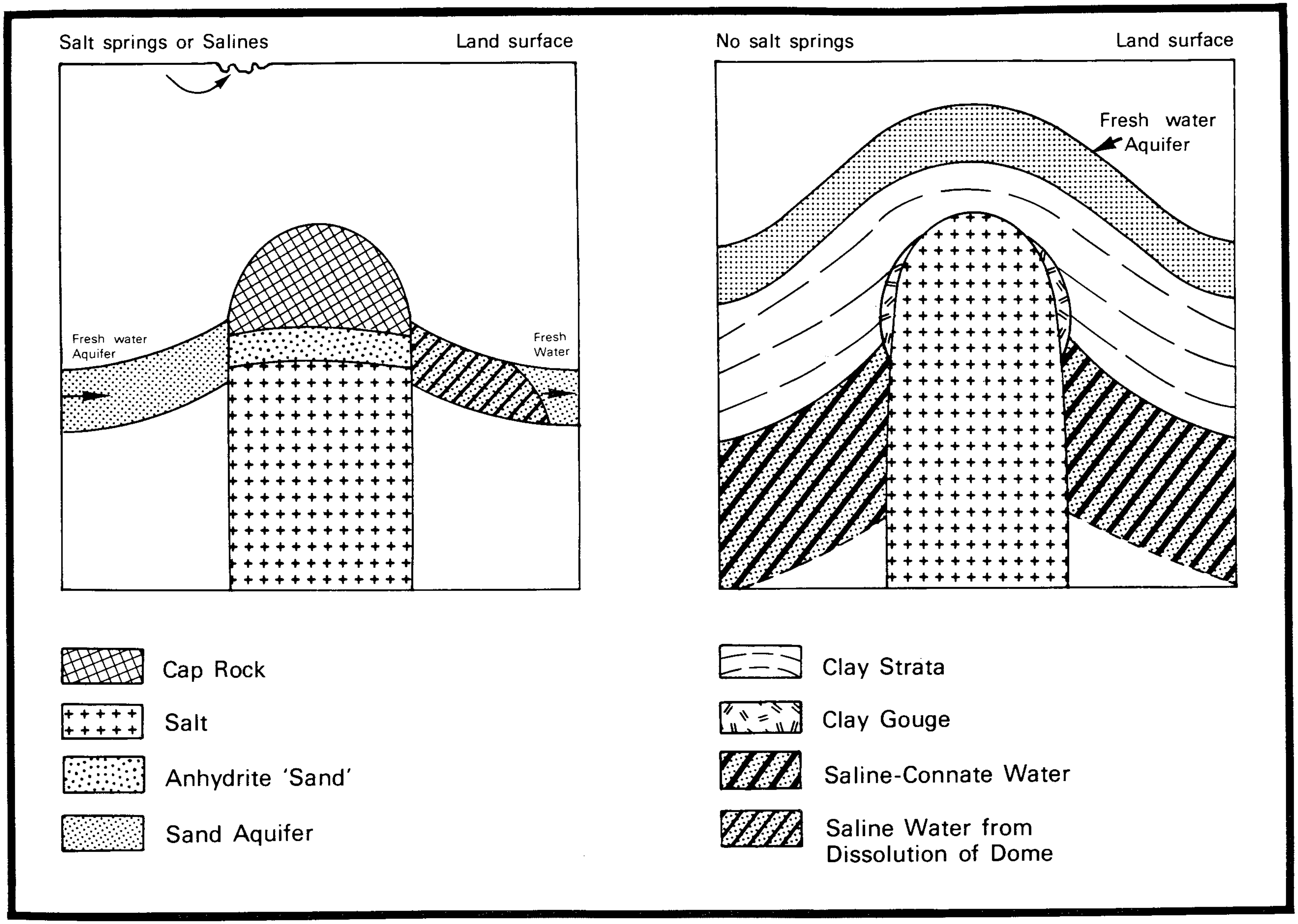


Figure 27. Contrasting conditions relative to possible hydrological stability on Gulf Coast salt domes (after Martinez and others, 1975).

NORTH LOUISIANA SALT-DOME BASIN

Structure and Geologic Framework

As a compact basin embracing only 13,000 sq. km between the Monroe and Sabine uplifts, the North Louisiana salt-dome basin represents the smallest of the five dome-bearing basins in the Gulf Coast region (fig. 23). The North Louisiana basin has developed with a northwest-southeast elongation along the general trend of the North Louisiana syncline, which more closely borders the Sabine uplift on the west. Farther to the north in Arkansas, where the updip limit of the Louann Salt is present, a series of bordering faults marks the northward extent of the broad North Louisiana syncline. To the south, the latter structure and the salt-dome basin itself are bounded by a zone of flexure that separates these features from the main Gulf Coast geosyncline, where thick Tertiary, especially Miocene, deltaic strata dip gulfward. The North Louisiana basin at this point plunges southeastward and opens out into the larger geosynclinal feature.

Studies by Kupfer (*in* Martinez and others, 1975), which were based on the earlier work of several investigators, showed that the North Louisiana basin is in fact two basins; the more northern component or Minden trough (or basin) is the smaller and is separated from the southern Winnfield trough (or basin) by a narrow, east-west-trending positive feature called the Bistineau bridge. The latter, a principal development during the Cretaceous, was vague to nonexistent during Tertiary sedimentation. The 19 salt domes discovered to date in this basin cover a relatively small area containing only 4 parishes (Bienville, Natchitoches, Webster, and Winn) (fig. 28) and are divided between the Minden and Winnfield troughs so that 5 are present in the former and 14 in the latter. Overprinted on this regional structural expression are a number of lower order structural features designated as ridges, arches, and subbasins (Kupfer and others, 1976). One interesting observation of this work is that salt domes and subbasins exhibit a one-to-one relationship; in other words, the known salt domes in the North Louisiana basin are found in downwarped subbasin areas. Kupfer (*in* Martinez and others, 1976) even raised the intriguing point that more domes may remain to be discovered here because there are areas in several subbasins having sufficient areal extent to contain additional domes. The latter, however, have not been detected by drilling or conclusively revealed by geophysics to date.

One difference recognized from the northern cluster of domes as compared to those in the Winnfield trough is that the former are centered along the axes of the subbasins, whereas the latter are more on the flanks of their subbasins. These relationships may be due to different growth histories or more irregular subbasins in the southern area (Kupfer, *in* Martinez and others, 1976).

The Shreveport Geological Society (1968) depicted a narrow, domeless trough that connects the North Louisiana salt-dome basin with the Louisiana portion of the Mississippi salt-dome basin. In that northeast part of Louisiana, there are 12 known salt domes, all of which lie to the south of the Monroe uplift. The nearest dome here lies more than 50 km east of the most easterly dome in the North Louisiana basin. Various regional features such as the Monroe uplift, the zone of flexure bordering the basin on the south, or thinness in the Louann Salt apparently prevented continuous growth of domes across this distance. Whatever the reasons, the two centers of salt-dome development are considered separate interior basins.

The stratigraphic succession present in the North Louisiana basin includes the Triassic-Jurassic sequence (fig. 24) typical for the entire Gulf Coast region. Overlying

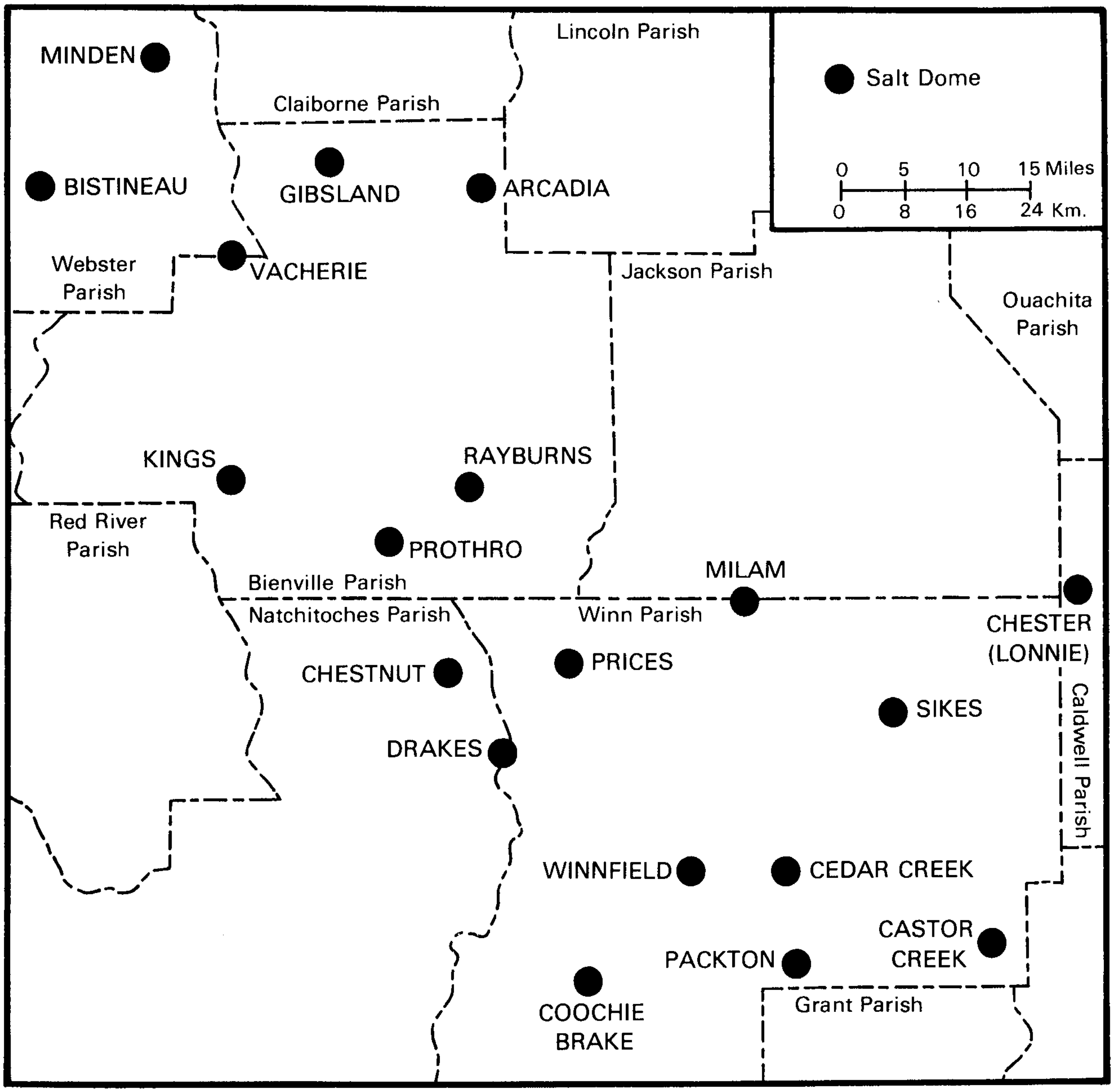


Figure 28. Map of North Louisiana salt-dome basin showing locations of 19 known and inferred salt domes (after Anderson and others, 1973; Netherland, Sewell and Associates, 1975a).

these older strata is a sequence of Lower and Upper Cretaceous and Tertiary units. The latter range through the Eocene (fig. 29); Quaternary terrace and alluvial deposits are also present throughout the basin. The sedimentary section ranges between 1,500 and 6,000 m in thickness (Shreveport Geological Society, 1968) and includes the subsurface type section for the very important Louann Salt. In general, the overall succession thins northward into Arkansas and westward against the Sabine uplift; thickness increases are observed in a southward direction toward the Tertiary depocenter.

The Late Jurassic–Cretaceous portion of the stratigraphic column is marine, contains various carbonate units (marls, chalks, other limestones), and exhibits pronounced facies changes that are related to the variations in thickness (Shreveport Geological Society, 1968). The Paleocene Midway Group is wholly a marine clay, whereas the younger Eocene Wilcox and Claiborne Groups consist of alternating sands and shales formed under fluctuating continental-deltaic-marine conditions.

Although the salt domes in this basin have never been of great significance to the petroleum industry, many of the other structures developed here, and in turn important for petroleum entrapment, are clearly related to salt flowage at depth. Anticlinal structures, faults, and even stratigraphic changes have been caused by movement in the Louann Salt and the effects of this movement on shallower beds. Conspicuously absent in the North Louisiana basin, however, are growth faults and their related depositional-fault systems, both of which are typical of the Texas-Louisiana coastal basin to the south. Of course, faulting around and on the tops of domes and on the flanks of dome-bearing subbasins, as well as strongly upturned strata near domes, represent structural features related to salt diapirism.

The specific geological literature pertaining to this basin is well summarized in the numerous references cited by Martinez and others (1975, 1976), in addition to the specific treatments provided by Murray (1961), the Shreveport Geological Society (1968), and Anderson and others (1973).

Salt Domes

Of the 19 known and suspected domes in the North Louisiana basin, 4 lie well below 1,000 m and thus are extremely deep, 4 are being presently utilized for LPG storage, and 1 (Minden) supports active petroleum production (table 1). The top of salt in Chestnut and Coochie Brake domes is below 700 m. Three domes, Castor Creek, Cedar Creek, and Price's, have not been penetrated by drilling (Martinez and others, 1976), although Anderson and others (1973) contended that salt had not been drilled at the Prothro dome. In the 5 shallow domes where salt has been encountered, the top of salt lies less than 320 m below the land surface at each; the depth is only 40 m at Rayburn's dome.

Cap rock has been encountered on all but four of the domes. Where cap rock has been developed, there is a fair degree of variability in thickness and thickness of cap rock relative to depth (Martinez, *in* Martinez and others, 1975).

Of the domes that currently are not too deep or used by industry, six have salines at the land surface above them. In the case of Castor Creek and Cedar Creek domes, where salt has not been detected by drilling, the presence of surface salines, a feature most typical of shallow domes, suggests that these domes may be similarly shallow.

Several salt domes here also display surface expression; Price's dome supports a small hill; the only exposed Upper Cretaceous strata in north Louisiana are present around Rayburn's and Prothro domes as the result of uplift; and other domes have

SYSTEM	SERIES	GROUP	FORMATION
QUATERNARY	HOLOCENE		Alluvium
	PLEISTOCENE		Prairie
			Montgomery
			Bentley
			Williana
TERTIARY	EOCENE	CLAIBORNE	Cockfield
			Cook Mountain
			Sparta Sand
			Cane River
		WILCOX	undifferentiated
	PALEOCENE	MIDWAY	Porters Creek Clay
			Clayton Limestone
CRETACEOUS	GULFIAN	NAVARRO	Arkadelphia Marl
			Nacatoch
		TAYLOR	Saratoga Chalk
			Marlbrook Marl
			Annona Chalk
			Ozan
		AUSTIN	Brownstown Marl
			Tokio-Ector Chalk
		WOODBINE – EUTAW	Eagle Ford Shale
		WOODBINE – TUSCALOOSA	Tuscaloosa
	COMANCHEAN	WASHITA	undifferentiated
			Kiamichi Shale
		FREDERICKSBURG	Goodland Limestone
		TRINITY	Paluxy
			Rusk-Mooringsport
			Ferry Lake Anhydrite
			Rodessa
			Pearsall
	COAHUILAN	NUEVO LEÓN	Sligo
			Hosston

Figure 29. Post-Jurassic stratigraphic succession in North Louisiana salt-dome basin (after Shreveport Geological Society, 1968; Anderson and others, 1973).

Table 1.–Features of Salt Domes in North Louisiana Salt-Dome Basin

	Depth to top of salt						Commercial utilization						
Dome Name	< 300 m	300–1000 m	1000–3000 m	> 3000 m	Cap rock encountered	Surface saline	Salt mine	Brine wells	Oil/gas production on dome	Hydrocarbon storage	Sulfur production	Surface mine
Arcadia		X			X					LPG		X
Bistineau		X			X	X		Abn.		LPG		
Castor Creek				N.D.		X						
Cedar Creek	X (?)				X	X						
Chester			X		X							
Chestnut		X			X							
Coochie Brake		X			X (?)							X
Drakes	X				X	X		Abn.		LPG		
Gibsland	X				X	X				LPG		
King's	X				X	X		Abn.				X
Milam			X		X							
Minden		X			X				X			X
Packton			X		X							
Price's				N.D.		X		Abn.				
Prothro	X (?)											Abn.
Rayburn's	X				X	X		Abn.				Abn.
Sikes			X		X							
Vacherie	X				X							X
Winnfield	X				X	X	X					X

N.D., not yet drilled; Abn., abandoned; LPG, liquefied-petroleum-gas storage; (?), presence of feature questionable or disputed.

Data from Hawkins and Jirik (1966), Halbouty (1967), Anderson and others (1973), Martinez and others (1975, 1976), Netherland, Sewell and Associates (1976a).

uplifted Eocene strata several hundred meters to expose older units (Wilcox) where the Claiborne Group is normally present at the surface. Several domes also exhibit central depressions above them.

The Winnfield dome was initially designated by Anderson and others (1973) as very dubious because of the (1) repetitive introduction of water into the salt-mine workings, both through the shaft and along other avenues; (2) presence of abundant carbon dioxide and interstitial brine in the salt; (3) repeated episodes of rock bursts in the salt mine owing to the pressurized carbon dioxide; and (4) evidence of active fresh-water interaction between the cap rock and salt as shown by past and recent subsidence there. The salt mine in this dome is completely flooded at present and has been for more than a decade. Although the degree of additional dissolution that has resulted from this event is not known, any future utilization of this dome, even if at greater depths, would very likely be confronted with serious problems of water encroachment and related salt dissolution.

The growth histories of selected domes, rates of overall salt diapirism, and relationships between salt tectonics and sedimentation in this basin have been studied by Kupfer and several of his graduate students at Louisiana State University (Martinez and others, 1975; 1976), using available well-log and geophysical data. By analyzing thickness changes in the various stratigraphic units affected by salt diapirs, the change in dips on formations adjacent to domes through geologic time, salt volumes involved, and the results of computerized trend-surface mapping of various subsurface units, Kupfer has been able to demonstrate the following:

(1) Salt movement, initially much of it in the horizontal dimension where it flowed into broad pillows and ridges, commenced in the Jurassic;
(2) by Early Cretaceous time, actual vertical diapirism had begun, development of rim synclines became pronounced, and as upward salt movement continued toward the surface, dissolution of salt also commenced;
(3) although individual domes show some variance, a pronounced diminution of vertical movement occurred by mid-Cretaceous time (approximately 100 million years ago) as shown by a significant slope change in plots of the dips of strata around certain domes;
(4) regionalized vertical movement ceased by the Early Tertiary, horizontal movement into the developed domes continued and then waned, but local arching and faulting of the strata above the domes continued into the Late Tertiary;
(5) cessation of salt movement in the Tertiary can be shown by an average value from calculations of several different parameters to have occurred about 25 to 30 million years ago, or in Miocene time; this agrees with the hypothesis that domes in this basin are tectonically stable and have not been active since the Late Tertiary;
(6) rates of salt movement as calculated on a volumetric scheme show a maximum in the Early Cretaceous of 0.16 cubic km of salt per million years, declining to values 0.1 of that by the end of the principal movement; conversion of an average volumetric rate to an uplift rate gives a value of 0.2 mm per year; and
(7) depending on whether the salt domes rose as entire stocks or as a series of separate spines (still a debated topic among Gulf Coast geologists; see articles by Kupfer, 1976; Wilson, 1977; Kupfer, 1977), the uplift rates would vary; for example, values for the Vacherie dome differ by a factor of 4, with spine-like movement being the faster.

Detailed studies of Quaternary deposits above certain domes are expected also to reveal whether any measurable uplift has occurred in the last 110,000 years. Tracing of a recognizable datum by means of analyzing data obtained from shallow boreholes and geophysical profiles are anticipated to provide resolution on this point (Martinez and others, 1976). Inasmuch as several North Louisiana salt domes lie below well-developed, central topographic depressions, a tentative view indicates, but does not yet prove, that there has been a lack of uplift during the Quaternary (Kolb, *in* Martinez and others, 1976).

Hydrology

Surface Water

Surface drainage in this basin is provided by four principal south-flowing streams named Bayou Dorcheat, Black Lake Bayou, Sabine Bayou, and Little River. Major streams that flank the basin are the Red River on the west and the Ouachita River on the east. The former receives the flow from the four streams cited and their dendritic tributaries, which traverse the rolling, hilly topography of the basin. Average annual precipitation approximates 125 cm, one-third of which ends up as runoff; a much smaller contribution recharges ground-water aquifers (Anderson and others, 1973).

Although the topographically high basin is generally well drained, swamps and marshy areas occur along stream courses and above certain salt domes that have central depressions at the surface. Despite the contention by Anderson and others (1973) that flood hazards seem to be low here, Martinez and others (1976) estimated that most domes show a potential for surface flooding at least 50 percent of the time. This view is predicated to a large degree on the swampy drainage above the domes as opposed to actual flooding from nearby streams. Despite its low potential for flooding because of good peripheral drainage, the Winnfield dome also has a lake (Spillway Lake) developed near it.

Although surface salines have been studied (Smith, *in* Martinez and others, 1976), the exact mechanism in all cases is not known. Possible explanations include (1) movement of saline connate water from strata upturned as the result of domal intrusion, (2) upward migration of saline water from the active dissolution of the salt stock, and (3) upward movement of saline brines from deeper aquifers whose complex hydrology has been partly or largely created by the presence of a salt diapir. Some evidence from the Northeast Texas basin appears to suggest that salines occur there where the aquifers overlying the domes are under sufficient artesian pressure. Upturned strata that can supply the brines also seem to be important in some cases.

Even though dissolution of the salt stock could also be involved, the surface salines at King's, Rayburn's, and Bistineau domes appear to be from brines which emanate from upturned Cretaceous strata. Salines at Price's and Cedar Creek domes, where both Tertiary and Cretaceous stratigraphic units are present above the salt masses, are more difficult to decipher. Castor Creek dome, at which Tertiary units are both horizontal and continuous across the dome and contain fresh water, is possibly the most difficult dome for which to explain the source of the brines involved in forming the saline. Additional drilling, chemical analyses of the salines themselves, and attempts to geochemically differentiate various saline waters may decipher the origin of surface salines and which ones indicate active dissolution.

Ground Water

The principal fresh-water aquifers in the North Louisiana basin are Eocene in geologic age and include sand zones in the Cockfield Formation, the Sparta Sand, and the Wilcox Group. The Sparta Sand is, however, the single most important aquifer. Cretaceous-age aquifers contain brackish to saline water (Rollo, 1960) and are separated from the overlying fresh-water zones in the Eocene by the Paleocene Midway Clay. Fresh water in these various aquifers is under artesian pressure except where the units are exposed; recharge is largely at the outcrop. The Cockfield aquifers are confined to the southernmost parish (Winn) in the basin, but the Sparta Sand aquifer is present over a much larger area. The Sparta Sand is also significant in Louisiana because it is a major source of discharge to the Mississippi River alluvial valley (Payne, 1968).

In general, the depth to fresh water increases within the basin in a southerly direction but shows a fairly irregular pattern owing to the influence on the east of the Monroe uplift and the presence there of the Midway Clay, the occurrence of salt domes, faulting, and differences in the depth of flushing (Anderson and others, 1973). For example, there is a 150-m rise in the depth to fresh water in aquifers of the Claiborne Group, apparently owing to the southernmost extent of flushing within those intervals. Because the depth-to-fresh-water surface is so much more irregular within the basin than in outlying areas that lack salt domes, Rollo (1960) felt that the influence of domes is a major contributing factor. He also ascribed differences in ground-water gradients on the south flanks of domes to the presence of these intrusive structures.

Considerable attention was devoted by Smith (*in* Martinez and others, 1975, 1976) to the study of the so-called hydrologic stability of salt domes in this basin. Principal approaches have entailed analysis of the responses shown on mechanical logs run in various boreholes and the chemical quality of water obtained from test wells. An emphasis has been placed upon the detection of saline plumes within normally fresh-water, Tertiary-age aquifers in the vicinity of domes. Where no salinity contamination was discovered, or where the impermeable Midway Clay separated the salt mass from the Tertiary aquifers, the domes were considered to be hydrologically more stable. Unfortunately, the data are not always conclusive, and some question exists whether, in heterogeneous sediments, especially those with appreciable carbonate content, log analysis can adequately detect salinity differences without supporting evidence from water-sample chemistry. Some question has also been raised whether saline plumes can only be caused by the dissolution of nearby salt domes.

The topic of hydrologic stability, especially where inconclusive data exist, thus remains a debatable point in regard to evaluating salt domes. Those domes that are shielded by a protective clay-shale sheath are clearly less likely to undergo ground-water dissolution and as such might represent potentially more favorable choices. On the other hand, dissolution of a salt dome, especially if the process is occurring at very slow rates and only near the current-day upper salt surface, may be analogous to the same condition in bedded deposits where distant dissolution may not unto itself reject that salt bed elsewhere. Critical here is the determination of the rate of dissolution, and whether that rate, as projected through time, could result in the removal of enough salt so that the integrity of any repository might be violated. Studies, in which monitoring of active dissolution and totally protected (by shale) domes is undertaken, are needed to resolve this most pressing question about dissolution rates.

Seismic Activity

No seismic activity above the level of intensity MM V has ever been recorded within the North Louisiana salt-dome basin (Coffman and von Hake, 1973). This area lies wholly within zone 1 on the seismic-risk map (see fig. 16) prepared by S. T. Algermissen (ESSA/Coast and Geodetic Survey, 1969).

Several events of intensity MM V and one event each of intensities VI and VII have been recorded, however, well to the north in Arkansas (see fig. 15). Major earthquakes associated with the New Madrid zone of Missouri-Illinois-Kentucky have displayed felt areas that have extended this far south, even though no major damage to surface facilities was observed. Nuttli (1973), for example, showed on isoseismal maps of the 1811–12 events that North Louisiana was within an area experiencing an intensity of value VII on the Modified Mercalli scale. What effect these large yet distant earthquakes had on the subsurface, or salt domes in particular, is not known.

Thomas and Manning (*in* Martinez and others, 1976) reported the deployment on the Vacherie dome of an array of tiltmeters and microseismic-monitoring equipment as part of a study on salt-dome tectonics. As well, a seismograph was to be utilized to aid in interpreting data from the other equipment. Among other things, this instrumentation package could provide information useful in understanding the response of salt domes to distant seismic events. Additional insight on such responses may also emerge from numerical modeling of salt domes conducted by these same investigators.

Outside of the possible effects from the New Madrid zone, seismicity in this basin appears to be of minimal concern, especially with regard to any facility located within the subsurface.

Mineral Resources

Oil and Gas

Commercial hydrocarbons have been produced from strata of Jurassic, Cretaceous, and Tertiary age in this basin. Jurassic and Cretaceous production from such formations as the Sligo, Rodessa, Paluxy, Tuscaloosa, Hosston, Schuler, and Smackover is associated with anticlinal structures caused by deeper salt flowage, fault traps, and stratigraphic (porosity) changes. Tertiary production is largely from the Eocene-age Wilcox Group in which sands, alternating with shales in this deltaic sequence, serve as reservoirs. Although the region is possibly better known for natural gas, especially the long-productive and prolific Monroe field, most of the petroleum from Wilcox-age reservoirs is in the form of crude oil (Shreveport Geological Society, 1968).

Only the Minden dome in this basin has supported associated petroleum production. Other domes here essentially lack any significant producing fields close enough to pose a competitive hazard for a waste repository. Netherland, Sewell and Associates (1975a), in assessing the overall petroleum potential of several domes in this basin, felt that adequate test wells have been drilled adjacent to these domes to establish their barren character with regard to present and future petroleum potential.

Salt

Data presented by Hawkins and Jirik (1966) and Halbouty (1967) reveal that salt in the form of brines was recovered during the Civil War from wells at Bistineau, Drakes, King's, Price's, and Rayburn's domes (table 1). Anderson and others (1973) indicated that the brines at Price's dome actually came from shallow salt springs or the saline at the surface. As reported by Martinez and others (1976), only one brine well was utilized at Rayburn's dome; the amount of production and the size of the ensuing cavity in the salt are not known. At present, no brines are being produced from any dome in the North Louisiana basin. Salt was mined by the Carey Salt Co. from underground workings at the Winnfield dome from 1932 to 1965. Since 1965, the mine has been completely flooded as the result of a large inflow of water now believed to have drained from a very porous zone immediately above the cap-rock–salt contact (Martinez and others, 1976). Although production of gypsum and anhydrite from the surface quarry in the cap rock has continued, no salt has been recovered from the Winnfield dome since the flooding. Prospects for reopening the mine are not good.

Arcadia, Bistineau, Drakes, and Gibsland domes are the only ones utilized for the storage of LPG hydrocarbons (Anderson and others, 1973; Martinez and others, 1976), and no additional storage facilities have been proposed for other domes to date.

Inasmuch as the salt-resource base in Louisiana is vast, as only one salt mine has even been developed in a dome in this basin, and as the prospects for future salt mines or LPG-storage facilities here are not great, the possible utilization of a dome for waste storage should not encounter significant competitive opposition.

Sulfur

Although 15 of the 19 known domes in this basin have developed cap rocks, native sulfur has never been produced from any of the latter. According to data tabulated by Anderson and others (1973), no sulfur mineralization has been reported on the eight domes they recommended for further study. No exploration conducted specifically to find sulfur appears to have been undertaken in the basin. A reasonable conclusion is that sulfur production from domes in this basin does not represent a future competitive usage.

Other Minerals

Sand and gravel and limestone are mined locally in the North Louisiana basin. Martinez and others (1976) reported that surface pits and small quarries at which these resources are or have been recovered are located near 8 of the 18 domes; this includes the cap-rock quarry at the Winnfield dome.

In the case of Prothro and Rayburn's domes, limestone from the uplifted Cretaceous Saratoga Chalk was produced from now-abandoned quarries located above the areas underlain by each dome. Thus, mining here did not involve the cap rock. Sand and gravel produced near King's and Vacherie domes have been mined from Quaternary deposits.

Despite cessation of salt mining at the Winnfield dome since 1965, production of gypsum and anhydrite from the cap-rock quarry has been maintained. Prior to recovering these resources, some limestone was also quarried at the site.

Inasmuch as the surface-mining operations within this basin are either abandoned or entail small-volume production, their presence does not represent a hazard or other reason for concern.

Regional Evaluation for Storage of Radioactive Waste

The 19 domes in this basin include 15 with salt in the optimum depth range of 300 to 1,000 m below the surface. Of these 15 domes, 4 have been adapted for LPG storage, 1 supports appreciable petroleum production, and 1 contains a mechanical salt mine that is currently flooded. The salt in two other domes, Castor Creek and Price's (detection of salt by drilling in Cedar Creek dome is also questionable), has not been encountered by drilling, but these domes are suspected to be shallow. Whether shallow or not, there is inadequate information available to evaluate them fully at this time.

Four of the remaining domes, Bistineau, Drakes, King's, and Rayburn's, sustained past production of brine, and the effect of man-made solution on the salt masses needs to be studied and evaluated. Preliminary evaluations have looked into the hydrologic stability of the more promising domes here, but a definitive resolution has not been possible to date. Detailed studies appear, however, to have shown that significant tectonic uplift of domes in this basin subsided by mid-Tertiary time; investigation of Quaternary deposits could eventually show that there also has been no recent movement of any consequence.

Thus, domes in this basin tend to be shallow, not extensively developed for competing industrial applications, and apparently devoid of any significant tectonic movement. Additional information needs to be acquired to evaluate the ground-water hydrology around the more promising domes, especially as it pertains to salt dissolution. Studies currently under way promise to provide a better understanding about the potential for storage in several domes here.

NORTHEAST TEXAS SALT-DOME BASIN

Structure and Geologic Framework

As part of the larger East Texas embayment, the Northeast Texas salt-dome basin represents an elongate, northeast-aligned tectonic and depositional feature centered near the city of Tyler. Approximately 160 km in diameter, the basin is bordered by the following major structural features: (1) Mexia-Talco fault system to the west, northwest, and north; (2) Sabine uplift to the east; and (3) Elkhart–Mount Enterprise fault system to the south. As shown in figure 30, the updip limit of the Louann Salt lies inside the Mexia-Talco fault zone; however, the Louann Salt thickens toward the center of the basin where the 18 piercement salt domes detected to date are concentrated. In this area, the depth to the top of the parent salt unit lies between 6,100 and 6,700 m. Between the bordering fault zone and the depocenter of the basin where the domes are clustered lies a northeast-aligned belt of anticlinal folds supported at depth by ridges developed through flowage in the deeply buried Louann Salt. Halbouty (1967) indicated that a narrow regional trough separates the Mexia-Talco fault zone and this zone of salt-supported anticlines.

Netherland, Sewell and Associates (1976a), through detailed subsurface mapping, have shown that the shallow piercement domes are located in troughs developed in the Louann interval, whereas the deep-seated domes are associated with ridges. Rim synclines are also well developed around most domes here (Nichols and others, 1968). Major faults, which affect Cretaceous strata more than do older or younger units, are associated with the flanks of the deep ridges (Netherland, Sewell and Associates, 1976a), whereas more localized, radial faults occur above various salt domes (Krusekopf, 1959). Strata uplifted at the surface around several domes also show pronounced dips in contrast to the generally gentle regional dip of the Tertiary strata into the basin.

Basement rocks here, not penetrated by drilling, consist of Paleozoic rocks, overlain in places by the Triassic Eagle Mills Formation, which is postulated to have developed within fault blocks in the underlying older sequences (Vernon, 1971). The Jurassic sequence, including the Louann Salt, is similar to that typical of the Gulf Coast region (fig. 24). Above the Jurassic is developed a thick sequence of Lower and Upper Cretaceous and Tertiary strata (fig. 31). Many units within the Cretaceous and the Paleocene Midway Group are calcareous and include marls, chalks, and other limestones. These carbonate units have been uplifted and exposed around several domes, such as Palestine, Keechi, and Steen (Anderson and others, 1973). The remainder of the Tertiary sequence consists of interbedded shales, clays, and sands deposited under both marine and continental conditions in a series of shifting deltaic regimes. Appreciable lignite was also formed within the Eocene Wilcox Group.

The Eocene succession is the most notable, because many of the domes have penetrated this sequence, which also contains the principal fresh-water aquifers. One local exception involves the Midway Group, whose clays may provide an envelope around the top of the Whitehouse dome (Anderson and others, 1973).

Selected articles about the stratigraphy, petroleum geology, and salt domes of the Northeast Texas salt-dome basin include those by Eaton (1956), Krusekopf (1959), Nichols (1964), Fisher (1965), Nichols and others (1968), Holcomb (1971), Newkirk (1971), Rainwater (1971), and Vernon (1971). These are in addition to the more recent reviews and evaluative reports by Anderson and others (1973), Martinez and others (1976), and Netherland, Sewell and Associates (1975a; 1976a).

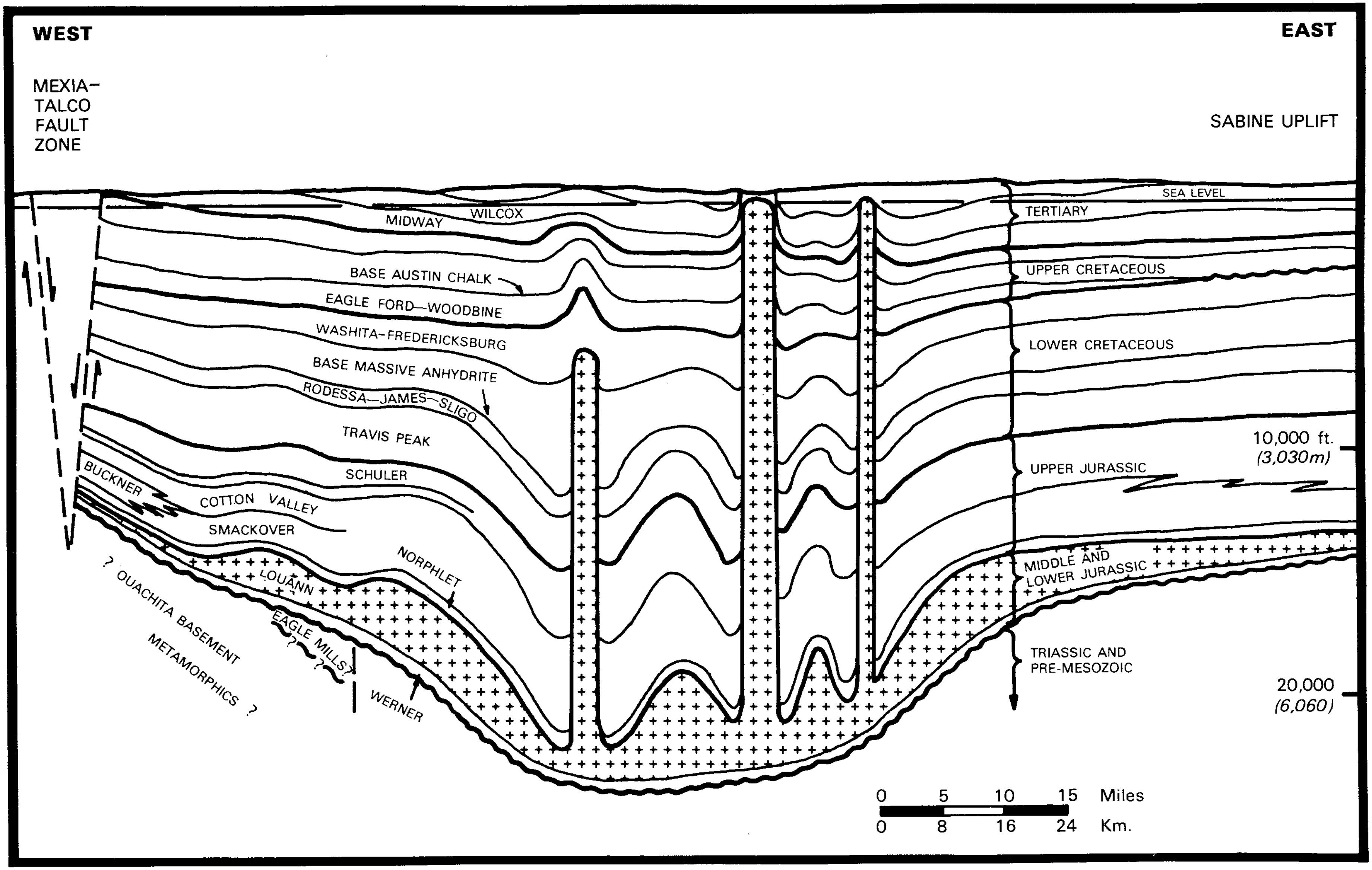


Figure 30. Diagrammatic cross section through Northeast Texas salt-dome basin showing generalized relationships between Louann Salt, salt domes, and stratigraphic succession. Pronounced vertical exaggeration makes domes and interdomal flank areas appear abnormally thin (after Netherland, Sewell and Associates, 1976a).

SYSTEM	SERIES	GROUP	FORMATION
TERTIARY	HOLOCENE		Alluvium
	PLEISTOCENE		Beaumont
			Lissie
			Willis
	PLIOCENE		Goliad
	MIOCENE		Fleming
			Catahoula
	EOCENE	JACKSON	Whitsett
			Manning
			Wellborn
			Caddell
			Moody's Branch
		CLAIBORNE	Yegua
			Cook Mountain
			Sparta
			Weches
			Queen City
			Reklaw
			Carrizo
		WILCOX	Sabinetown
			Calvert Bluff
			Simsboro
			Hooper
			Seguin
	PALEOCENE	MIDWAY	Wills Point
			Kincaid
CRETACEOUS	GULFIAN	NAVARRO	Kemp Clay
			Corsicana Marl
			Nacatoch Sand
			Neylandville Marl
		TAYLOR	Upper Taylor
			Pecan Gap Chalk
			Wolfe City Sand
			Lower Taylor
		AUSTIN	Austin Chalk (=Tokio-Ector Chalk)
		EAGLE FORD	Eagle Ford
		WOODBINE	Lewisville
			Dexter
	COMANCHEAN	WASHITA	Maness Shale
			Buda Limestone
			Grayson Shale
			Georgetown
		FREDERICKSBURG	Kiamichi Shale
			Goodland-Edwards Lst.
		TRINITY	Paluxy
			Upper Glen Rose
			Massive Anhydrite
			Lower Glen Rose
			Travis Peak

Figure 31. Post-Jurassic stratigraphic succession in Northeast Texas salt-dome basin (after Nichols and others, 1968; Netherland, Sewell and Associates, 1976a).

Salt Domes

Eighteen salt domes have been discovered via drilling in the Northeast Texas basin (fig. 32). Although Anderson and others (1973) grouped, for convenience, Day and Kittrell domes with their tabulations with this basin, these two domes are actually part of the Texas-Louisiana coast salt-dome basin. Netherland, Sewell and Associates (1976a) also listed five additional domal features whose deep-seated salt had not been encountered by drilling; these postulated domes are not included in this discussion either.

As tabulated in table 2, 4 domes are below the optimum depth, as their upper salt surfaces lie below 1,000 m; 3 others have prolific, associated petroleum production; 3 are being used for LPG storage; and 1 has had multiple industry usage. With the exception of Whitehouse dome, the depth to salt in the remaining 7 domes is shallow, being less than 200 m in all cases. The shallowest is in Palestine dome, whose top of salt rises to slightly more than 30 m below the land surface. Cap rock has been detected on 11 of the domes in this basin but may be developed on others where data are lacking (Martinez, *in* Martinez and others, 1975).

Brooks dome is now overlain at the surface by a sizable arm of Lake Palestine; this fact obviously introduces a potential hazard of flooding from such a sizable body of surface water. Even though mining is safely conducted within the subsurface under lakes and other large accumulations of water, the location of a waste repository at such a site needs to be viewed much more cautiously. In addition, Lake Palestine supports several resort-recreation developments, and their presence mitigates further against the favorability of this dome.

There is also a shallow saline lake, called the Old Salt Works Lake, above Palestine dome. Abandoned brine production here could be another point of concern owing to a lack of complete knowledge about old well locations and the effect of man-made dissolution on the salt mass. These aspects, therefore, cast some doubt on this dome's potential, but detailed study could ameliorate such concerns.

Salt domes here range from 1.5 to 8 km in diameter and are believed to be attached still to the Louann Salt at depths upward of 6,700 m in the center of the basin. Calculation of "uplift-versus-time" values for these domes has indicated that growth rates varied unevenly through geologic time, decreased through time as the centers of more pronounced sedimentation shifted southeastward, and averaged 0.006 mm of uplift per year over the last 50 million years or since Wilcox time (Netherland, Sewell and Associates, 1976a). As shown by these studies, uplift commenced in Jurassic time but appears not to be under way at present. These conclusions have been reached, however, on the basis of detailed subsurface studies alone. If Late Cenozoic (Quaternary or Holocene) movement has occurred, doming or warping of alluvial and terrace deposits could provide evidence of this phenomenon; studies of such deposits with that objective have been proposed (Netherland, Sewell and Associates, 1976a).

Hydrology

Surface Water

Average annual precipitation in this part of Texas is approximately 110 cm. Most of this arrives as runoff to the east-flowing Sabine River, or to the southeast-flowing Neches and Trinity Rivers. Into these major streams flow numerous tributaries that are arranged in a dendritic pattern on the gently rolling topography of the basin. Drainage is

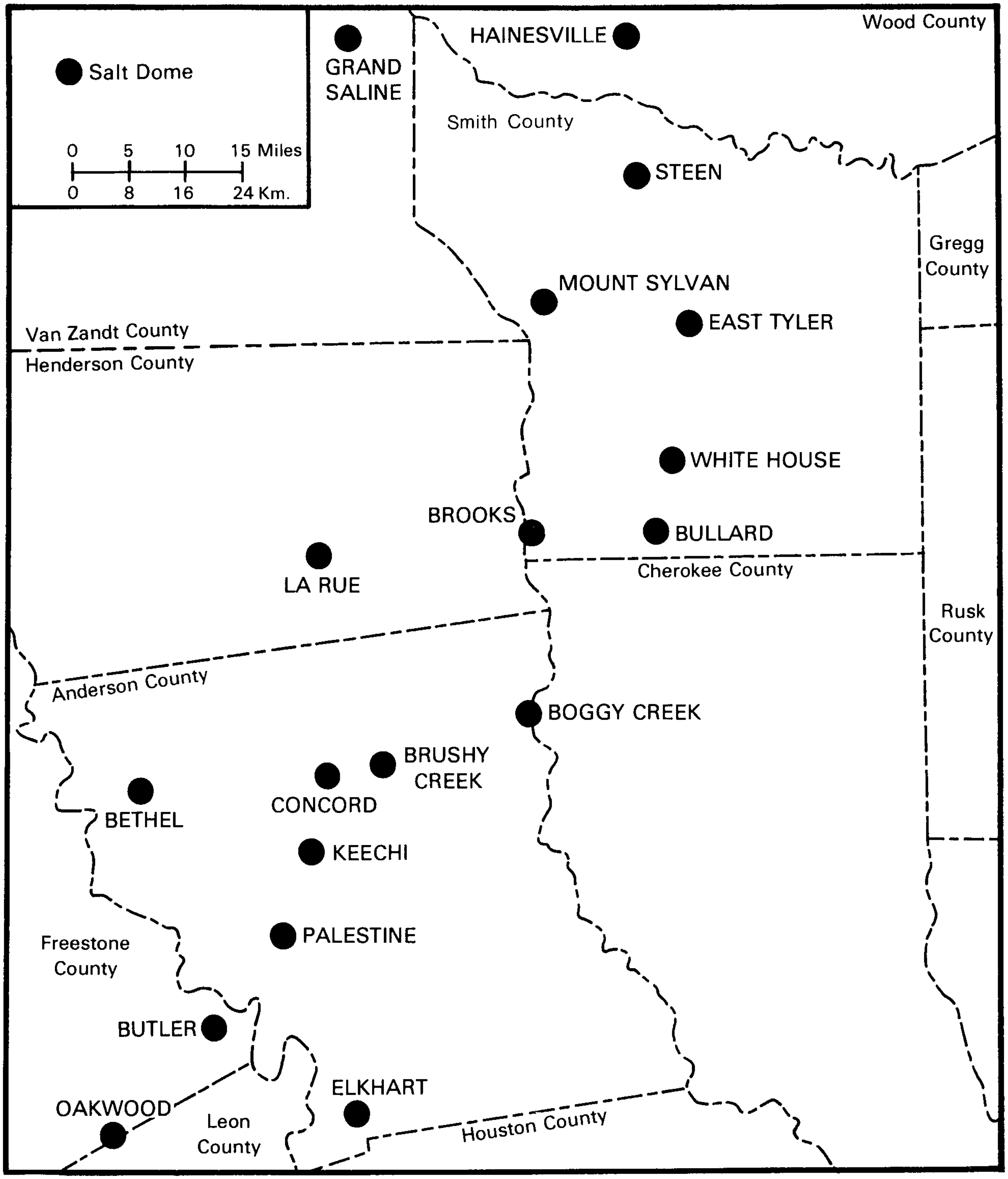


Figure 32. Map of Northeast Texas salt-dome basin showing locations of 18 known salt domes (after Anderson and others, 1973; Netherland, Sewell and Associates, 1975a).

Table 2.-Features of Salt Domes in Northeast Texas Salt-Dome Basin

	Depth to top of salt						Commercial utilization					
Dome Name	< 300 m	300—1000 m	1000—3000 m	> 3000 m	Cap rock encountered	Surface saline	Salt mine	Brine wells	Oil/gas production on dome	Hydrocarbon storage	Sulfur production	Surface mine
Bethel		X			X				X			
Boggy Creek		X							X			
Brooks	X				X	X		Abn.	Abn.			Abn.
Brushy Creek			X		X							
Bullard	X				X							
Butler	X								Abn.	LPG		X
Concord			X						X			
East Tyler	X				X					LPG		
Elkhart				X					Abn.			
Grand Saline	X				X	X	X	Abn.	X			
Hainesville		X							Abn.	LPG		
Keechi		X			X	X (?)						
La Rue			X									
Mount Sylvan	X				X (?)	X						
Oakwood	X				X				X			
Palestine	X				X	X	Abn.	Abn.				Abn.
Steen	X				X	X		Abn.	Abn.			Abn.
Whitehouse	X				X							

Abn., abandoned; LPG, liquefied-petroleum-gas storage; (?), presence of feature questionable or disputed.

Data from Hawkins and Jirik (1966), Halbouty (1967), Anderson and others (1973), Martinez and others (1975, 1976), Netherland, Sewell and Associates (1976a).

generally good except for localized marshy and swampy areas along various stream courses.

Damming of the Neches River has given rise to the formation of Lake Palestine, and, as previously noted, this hydrologic feature now overlies the surface area above Brooks dome. This dome previously had a surface saline above it prior to inundation by the lake. In addition to lacking surface salines, Bullard and Whitehouse domes are also devoid of swampy terrain above them at the land surface, and Palestine dome similarly lacks an overlying swampy area (Martinez and others, 1976). These investigators felt that only Brooks dome, because of Lake Palestine, and Steen dome, because of an overlying swampy area and a nearby stream, are considered prone to flooding more than 50 percent of the time. Proximity of Mount Sylvan dome to the flood plain of the Neches River might increase the possibility of flooding above this dome despite the low value of flooding potential cited by Martinez and others (1976). The saline lake above Palestine dome, despite its shallow depth, needs to be considered seriously whenever this dome is more fully evaluated.

Ground Water

Definitive studies of the ground-water resources in the dome-bearing part of the basin are contained in articles by Dillard (1963), Guyton and Associates (1972), and White

(1973). Evaluative reports about the ground water and its relationships to salt domes here are those by Anderson and others (1973), Netherland, Sewell and Associates (1976a), and Martinez and others (1976).

Principal fresh-water aquifers occur in the Eocene-age sequence and include sands within the Wilcox Group and within the Carrizo, Queen City, and Sparta Formations of the Claiborne Group. All these units reveal very high well yields (Anderson and others, 1973). The regional ground-water flow direction, where artesian conditions away from the outcrop belt persist, is toward the southeast. In general, the base of fresh water agrees with the base of the Wilcox Group, which lies at a depth of nearly 700 m in the center of the basin, although there is considerable relief on this surface throughout the region. Some distortion of the flow direction in the Wilcox Group aquifers can be observed near salt domes (Smith, *in* Martinez and others, 1976).

Underlying the Wilcox Group is the impermeable Midway Clay, which prevents vertical communication between deeper, saline aquifers and the fresh-water Tertiary aquifers. As well, the Midway prevents contact between circulating fresh gound water and salt domes where the latter do not penetrate this interval or where a sheath of this clay, uplifted by the dome, surrounds the salt stock, thus apparently preventing dissolution. Such appears to be the case at Mount Sylvan dome, even though the surface salines above this dome are more difficult to explain when that circumstance is taken into account.

Fresh-water aquifers within the Wilcox Group are especially significant in this basin, because they are the only units to have potential connection with salt domes and hence to contain saline plumes. Dillard (1963) reported that decreases in water quality within the Wilcox Group near the city of Tyler in Smith County are caused by dissolution of nearby salt domes. Some saline contamination near the Grand Saline dome may be related, however, to oil-field brines (Netherland, Sewell and Associates, 1976a).

Also significant here is the deeper Woodbine Formation, whose sands contain saline water shown by Parker (1969) on a regional basis not to be the result of salt-dome dissolution. The Woodbine Formation commonly serves as an injection zone for the disposal of oil-field brines, and this unit could receive artificially solutioned brines as well. The depth to this stratigraphic unit is generally between 1,500 and 1,600 m.

Smith (*in* Martinez and others, 1976) found the following hydrologic information about those salt domes that are shallower than 1,000 m and not utilized for various industrial applications:

(1) Saline plumes appear to occur in the Wilcox Group aquifers at Bullard, Steen, and Whitehouse domes;
(2) Brooks, Keechi, and Palestine domes raised both Cretaceous and Wilcox Group units to the surface, and thus the Midway Clay protects these domes from dissolution by Wilcox Group aquifers;
(3) Mount Sylvan dome does not pierce the Midway Clay and hence appears to be protected from dissolution as a result;
(4) surface salines or salt springs occur above Brooks, Keechi, Mount Sylvan, Palestine, and Steen domes;
(5) salines at Mount Sylvan and Steen domes appear to be related to a potentiometric surface in the Wilcox Group that is higher than the top of these domes; those at the other three domes appear to be associated with uplifted and exposed Cretaceous strata.

In a preliminary sense, Smith felt that Brooks, Keechi, Mount Sylvan, and Palestine domes were more hydrologically stable, but he cautioned that the surface salines above Brooks and Palestine domes could indicate active salt dissolution. Bullard, Steen, and Whitehouse domes were thought to be hydrologically less stable, largely on the basis of the saline plumes detected in the adjacent fresh-water aquifers of the Wilcox Group. Data were not adequate, however, to establish clearly the rate of dissolution nor abundant enough to eliminate conclusively alternative explanations for the observed hydrologic circumstances.

Seismic Activity

This is the only salt-dome basin in which an epicenter for an earthquake is actually known to be located. In 1932, an event registering an intensity of V on the Modified Mercalli Scale occurred near the eastern margin. Two other events, one of intensity V and the other of intensity VII, were also recorded east of the basin (Coffman and von Hake, 1973). As shown in figure 15, several earthquakes have also occurred well to the north of the basin in southeastern Oklahoma and to the northeast in south-central Arkansas. From the seismic-risk map (see fig. 16) of S. T. Algermissen (ESSA/Coast and Geodetic Survey, 1969) the Northeast Texas basin can be seen to lie within zones 0 and 1, where no earthquake damage and minor earthquake damage can be expected, respectively.

The cause of the 1932 event is not known, nor has any relationship to a nearby salt dome been established. The events to the east of the basin appear related to either regional fault systems or the adjacent Sabine uplift, although no definite relationship has been established here either.

Farther to the east, a total of six epicenters have been defined near the Sam Rayburn Reservoir along the Texas-Louisiana border since 1964 (Coffman and von Hake, 1973; Anderson and others, 1973). Because there is a good possibility that these low-intensity events are related to crustal loading from the reservoir impoundment, and thus represent induced seismicity, they are considered not to be as significant as natural earthquakes. In addition, these supposedly induced events are concentrated well to the east of the basin.

On the basis of this relatively low level of seismic activity, the potential for damage to surface facilities or subsurface features such as shafts appears to be minimal.

Mineral Resources

Oil and Gas

The Northeast Texas basin, commonly also called the East Texas basin, is well known in the annals of the domestic petroleum industry as one of the most prolific oil and gas regions in the country. The famous East Texas field, located along the eastern margin here and adjacent to the Sabine uplift, represented the nation's largest oil field until 1968, when the Prudhoe Bay field was discovered in Alaska.

Production in this basin has been established throughout the stratigraphic sequence of Jurassic, Cretaceous, and Tertiary units. Significant productive intervals include the Smackover, Bossier, Travis Park, Paluxy, Lower Glen Rose (Pettel and Rodessa members especially), Woodbine, and Tokio formations. The Woodbine is possibly the most noteworthy, because it is the reservoir in the East Texas as well as in other major fields. Lesser production has come from the Wilcox and Claiborne Groups. Nichols and others (1968) summarized the production and stratigraphic characteristics of the reservoirs in this basin.

Along the west and northwest, faults within the Mexia-Talco zone form important traps, whereas along the eastern margin, stratigraphic traps, typically with a regional structural component, are responsible for many accumulations, including the East Texas field. Within the more central parts of the basin, anticlines, faults, and salt diapirs serve as traps; these structures have been caused by flowage of the deeper Louann Salt. Between the Mexia-Talco zone and the basin center, salt-controlled anticlines also form important traps.

Some production of petroleum has been demonstrated on or closely adjacent to approximately one-half of the salt domes in the basin. Boggy Creek, Oakwood, Bethel, and Concord domes have been the most productive, in the order listed (Halbouty, 1967). Much smaller quantities of oil and gas have been recovered from fields associated with or located near Brooks, Brushy Creek, East Tyler, Elkhart, Grand Saline, Hainesville, Mount Sylvan, and Steen domes. Production at Brooks and Steen domes came from the Lower Cretaceous Paluxy Formation, but it has now ceased (Netherland, Sewell and Associates, 1975a). At Brooks dome, the field, located above the dome proper, sustained less than 200,000 liters ($<$1,200 barrels) of production; that at Steen has been about 10 times as productive but lies some 2.5 km away from the dome. Production associated with Mount Sylvan dome is also from the Paluxy but is of significantly greater volume even though the field is nearly 5 km from the dome. There is one abandoned well nearer the dome, but production from its Rodessa reservoir was meager. No petroleum has ever been discovered on Bullard, Keechi, Palestine, or Whitehouse dome (table 2). According to data tabulated by Netherland, Sewell and Associates (1975a), some 38 dry holes have already been drilled on or close to these shallow domes. The area surveyed for each dome was a circle centered at the dome and having an 8-km diameter. Several fields that produce from various Cretaceous reservoirs are, however, located near each of these domes; the closest is a sizable, multipay field less than 1.5 km south of Palestine dome.

Exclusive of previously cited Palestine dome as well as Brooks dome, the petroleum potential of the five other domes—Bullard, Keechi, Mount Sylvan, Steen, and Whitehouse—was evaluated by Netherland, Sewell and Associates (1976a) and found to be quite low. These investigators have stated that (1) adequate shallow, and in some cases, deeper, test drilling has been done on these domes without success; (2) untested zones and/or fault segments near the domes do not show much promise, based on the lack of success elsewhere on these diapirs; (3) deeper zones or other untested intervals more removed from the domes also show little promise, based on other drilling experience in the area; and (4) if deeper zones are to be adequately tested and shown to be productive, exploratory drilling to accomplish these objectives will be sufficiently distant from the domes so as not to pose any competitive usage or hazard to a possible storage site.

In summary, most domes originally considered promising by Anderson and others (1973) appear sufficiently barren of hydrocarbons or low in future petroleum potential that oil and gas activities should not interfere with, or in turn be interfered by, a waste-storage facility located in any one of them.

Salt

At present, salt is produced only from a subsurface mine operated by the Morton Salt Co. in the Grand Saline dome. Prior to rock-salt mining, salt was also recovered here from salt springs and brine wells. The latter are now abandoned, although a surface-collapse feature did develop in 1976 around the casing of one such old well (Smith, *in* Martinez and others, 1976).

In the past, especially during the Civil War, artificial brines were recovered through wells drilled into Brooks and Palestine and possibly Steen domes (Hawkins and Jirik, 1966). Although the facilities are presently abandoned, different episodes of brining at Palestine dome have resulted in the generation of several collapse sinkholes (Anderson and others, 1973). A dry-salt mine yielded a small tonnage of salt several decades ago and is also abandoned. Brines recovered in Civil War times at Steen dome may have been in part or totally natural, as production appears to have been from saline springs above the dome and not the salt mass itself (Smith, *in* Martinez and others, 1976).

Caution should be exercised in regard to Palestine dome because of the evidence of subsidence and solution disturbance to the salt surface related to the past salt brining. Sudden surface collapses like the one at Grand Saline dome might be possible here as well. The potential hazard is magnified by the unknown locations of most of the old wells (Netherland, Sewell and Associates, 1976a).

Three domes—Butler, East Tyler, and Hainesville—have been adapted for LPG storage, and the salt mine at Grand Saline dome is being considered for crude-oil storage. Possible competitive usage for hydrocarbon storage would not seem pressing at this time in light of other acceptable sites.

The current utilization of domes here for the production of salt or hydrocarbon-storage facilities does not seem to pose an overly competitive situation for a possible storage site.

Sulfur

No sulfur has ever been produced from any of these domes. There is furthermore no evidence that native-sulfur mineralization has been detected in encouraging amounts in any cap rock. The apparent conclusion at this time is that sulfur recovery from domes in the Northeast Texas basin does not now nor in the future represent a type of competitive usage.

Other Minerals

Limestone, sand and gravel, clays, and lignite are additional mineral resources that have been mined or are being recovered now within the basin. Although no cap-rock quarries have been developed here, small limestone quarries were previously productive at both Brooks and Steen domes. In the former dome, the Austin Chalk was quarried, while carbonate units of the Wilcox Group were mined in the latter. Both these operations are abandoned and made no negative impact on the domes beneath them. As reported by Fisher (1965), limestones exposed around Palestine dome show some promise as a potential future resource, but these units have not been mined to date.

Sand and gravel resources are widely distributed throughout the basin and are recovered primarily from stream-terrace deposits. Well to the east in the basin, coastal-terrace sands and gravels are mined. Although some sand and gravel have been mined southwest of Tyler in an area of several domes, the facilities were not close to any specific dome and thus no impact from the small surface workings was made.

A variety of clays used in several industrial applications have either been recognized or mined in this basin. No active or abandoned pits are near any of the more promising domes; but a number of occurrences in the general vicinity were cited by Fisher (1965). These surface operations, however, are not envisioned as posing any hazard to any subsurface salt dome.

Eocene lignites, especially within the Wilcox Group, extend from southeast Texas into the Northeast Texas basin and are being increasingly strip mined as fuel for the generation of electricity at utility and industrial power plants (Kaiser, 1974). Potentially important lignite deposits are concentrically distributed around Palestine dome and could become the site of future energy-resource development. In the early 1900's, lignite was mined here and used as fuel in the production of salt. Although large and valuable deposits of lignite lie both to the east (around Henderson in Rusk County) and west (near Athens in Henderson County) of the general Tyler-Palestine trend, where several domes are centered, development, either current or future, would not interfere with the subsurface usage of these domes. In the case of the Palestine dome, however, the proximity of the deposits would probably restrict usage of the dome during the time that any strip mining of that lignite was under way.

If any of the Texas lignites were to be gasified by means of *in-situ* gasification, as has been proposed, there is no such concern for this basin, as it lacks the deeper lignites required for such gasification (Kaiser, 1974).

Regional Evaluation for Storage of Radioactive Waste

The Northeast Texas basin embraces 18 known salt domes, 14 of which contain salt within the optimum depth range of 300 to 1,000 m. Three of these domes are used, however, for LPG storage, and three others sustain significant petroleum production. Grand Saline dome is utilized for rock-salt production and sustained appreciable brine production in the past.

Of the remaining seven domes, Brooks dome is a questionable choice owing to a large lake and resort developments at the land surface above it. Only Whitehouse dome of the six other domes lacks a surface saline, a feature that has been studied intensively here to ascertain whether the presence of this surface feature indicates dissolution of the salt mass or not. Because mechanisms other than salt dissolution have been shown to be possible explanations for surface salines, a more thorough analysis of the overall groundwater hydrology around any dome that has a saline at the surface is necessary to evaluate more clearly the hydrologic stability. As an example, the presence of an impermeable sheath of the Midway Clay at Mount Sylvan dome might provide additional confidence in this dome, despite the presence of surface salines above the dome.

The past use of Palestine dome for the production of rock salt and brine must also be taken into account in evaluating the potential of this dome. Aside from this, there exists a need for much more subsurface and hydrologic data to evaluate this and the other five more promising domes more fully. Preliminary studies have indicated initially, however, that tectonic movement in domes here ceased in the mid-Tertiary, a condition that makes the domes here of more interest than those in the coastal basins.

MISSISSIPPI SALT-DOME BASIN

Structure and Geologic Framework

As one of three interior salt-dome basins, the Mississippi basin extends east-southeast from northeast Louisiana across Mississippi into southwestern Alabama for a distance of 400 km. To the northwest, the basin abuts the Monroe uplift and is flanked along its north-northeastern and southern boundaries by the Pickens-Gilbertown fault zone and by the Wiggins arch–South Mississippi uplift, respectively. The presence of the Jackson dome has also affected the basin outline along its north border south of the Pickens-Gilbertown fault zone. The updip limit of the Louann Salt lies slightly to the northeast, roughly parallel to the north margin of the basin.

The basin is astride the point where the Appalachian and Ouachita tectonic belts are projected to merge in the Paleozoic basement that underlies the northern margins of the Gulf Coast basin. A deep, decidedly asymmetric structural depression has developed here, as indicated by a north-south cross section (fig. 33) on which the basin's structural axis is shown to lie well south of the geographic axis. At this point, the top of the Louann Salt is postulated to be below 6,400 m, while along the north flank the depth is only 3,165 m (Williams, 1969). Furthermore, there is little structural expression of the basin itself within the Tertiary sequence, which dips from 4 to 20 m per km toward the Gulf of Mexico and reflects more the influence of the regional Gulf Coast basin and Mississippi embayment.

From a physiographic standpoint, the northwestern part of the basin lies within the alluvial plain of the Mississippi River, whereas the remainder is within the Gulf Coastal Plain. In the former, a veneer of Quaternary alluvial deposits, which average some 60 m in thickness, mantles Tertiary strata; thin Pleistocene sand and gravel locally overlie exposed Tertiary units in the latter province. The Tertiary sequence consists largely of poorly consolidated sandstones with interbedded shales and lesser amounts of carbonates, particularly marl, formed under fluctuating deltaic conditions. Strata ranging from the Paleocene-age Midway Group to the Pliocene-age Citronelle Formation make up the Tertiary, which in turn is underlain by a thick sequence of Cretaceous and Jurassic strata (fig. 34). Eargle (1968) showed that this stratigraphic succession exceeds 6,000 m in thickness in the southern, and deepest, part of the basin.

In a gulfward direction across the basin, Miocene and younger strata become more clay-rich and thicker; in fact, several units increase significantly in their clay-shale content within the southern half of the basin. Because depocenters shifted through time and deltaic-stream systems gave rise to varying facies changes, the Tertiary stratigraphy tends to be more complicated than that of underlying sequences.

Salt Domes

The Mississippi salt-dome basin contains 77 known and suspected salt domes, of which 4 have not been encountered to date by drilling (fig. 35). Domes within this basin tend to be generally deeper, as shown by these data: (1) the tops of the 10 domes originally recommended by Anderson and others (1973) all lie below 400 m; (2) the tops of only 2 domes are shallower than 300 m in depth; (3) the tops of more than 12 domes lie below 3,000 m; and (4) 20 of the 34 domes whose tops are below 300 m are actually deeper than 600 m (table 3).

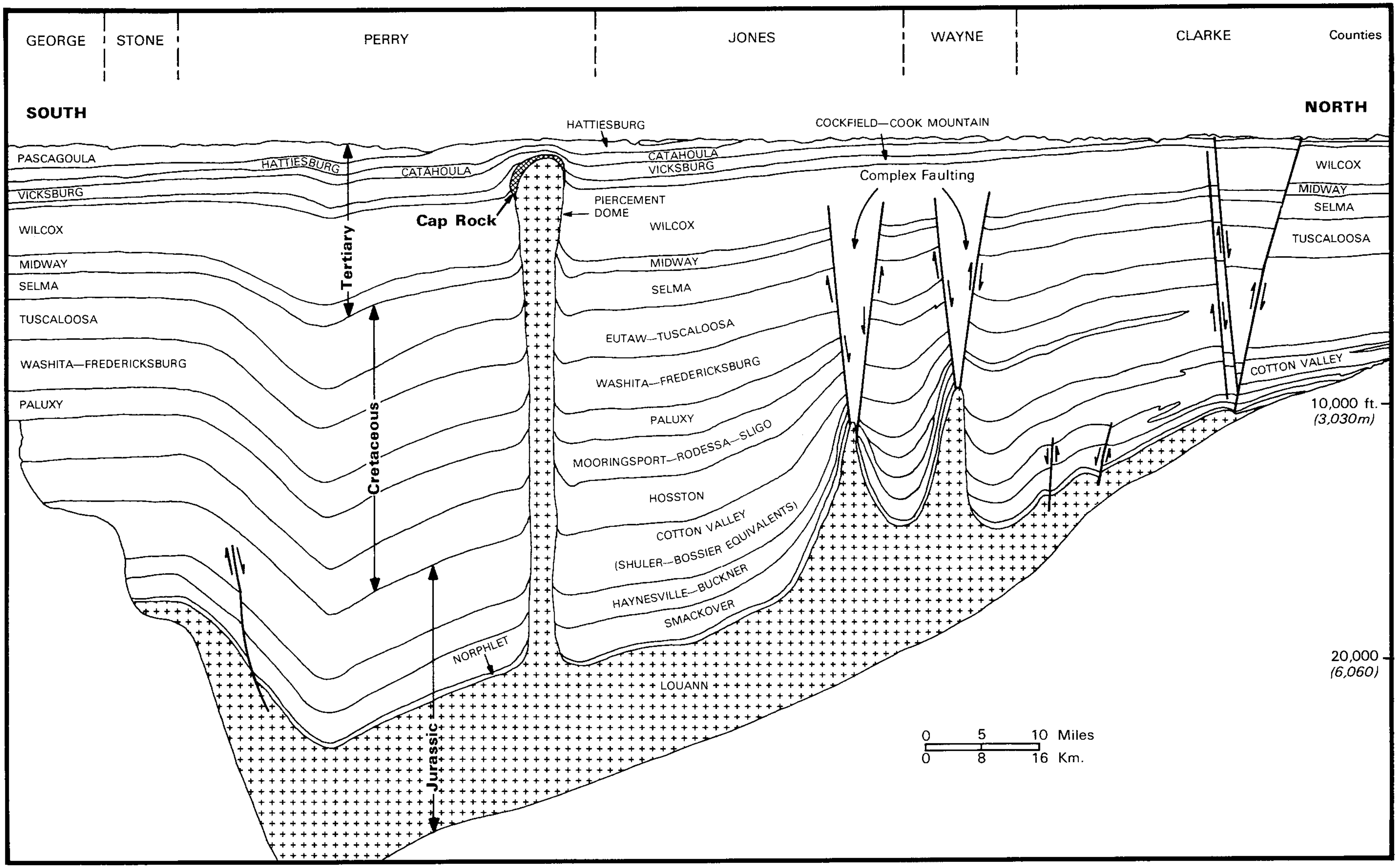


Figure 33. North-south cross section of Mississippi salt-dome basin showing basin's asymmetric configuration and restricted distribution of piercement salt domes (after Williams, 1969; Netherland, Sewell and Associates, 1976b).

SYSTEM	SERIES	GROUP	FORMATION
TERTIARY	PLIOCENE		Citronelle
	MIOCENE		Pascagoula Hattiesburg
			Catahoula Sandstone Paynes Hammock
	OLIGOCENE		Chickasawhay Limestone
		VICKSBURG	Bryam Marl Marianna Limestone Red Bluff Clay
	EOCENE	JACKSON	Yazoo Clay Moodys Branch
		CLAIBORNE	Cockfield Cook Mountain Limestone Sparta Sand Zilpha Clay } (Cane River) Winona Marl } Tallahatta Shale
		WILCOX	Tuscahoma
			? Nanafalia
	PALEOCENE	MIDWAY	? Naheola
			Porters Creek Clayton Limestone
CRETACEOUS	UPPER	NAVARRO	Selma-Eutaw
		TAYLOR	
		AUSTIN	
			Eagle Ford
		TUSCALOOSA	Coker-Gordo
	LOWER	WASHITA	Dantzler
		FREDERICKSBURG	Andrew Limestone
		TRINITY	Paluxy
			Mooringsport
			Ferry Lake Anhydrite
			Rodessa-James-Pine Island
			Sligo
			Hosston

Figure 34. Post-Jurassic stratigraphic succession in Mississippi salt-dome basin (after Eargle, 1968; Shell Oil Co., 1975; Netherland, Sewell and Associates, 1976b).

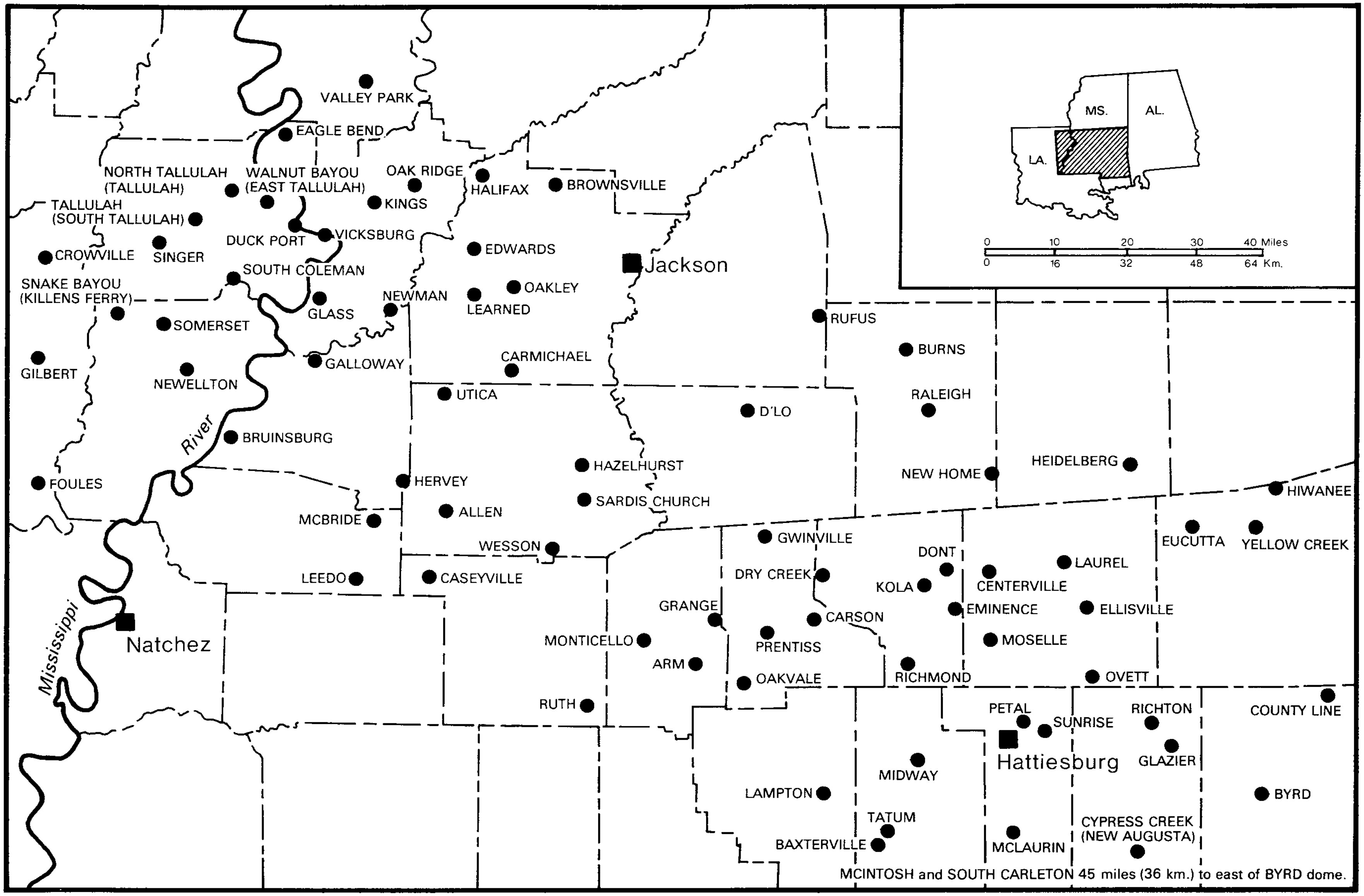


Figure 35. Map of Mississippi salt-dome basin showing locations of its 77 known and inferred salt domes (after Anderson and others, 1973; Netherland, Sewell and Associates, 1975a).

The distribution of domes in relation to depth is irregular, and the shallower domes are concentrated within the southern part of the basin. No domes within the northern half have tops shallower than 600 m. Because the latter area lies closer to the updip limit of the Louann Salt, the greater depth to domes there may be related to an inadequate supply of salt. Inasmuch as some 58 domes in the basin have developed cap rock (Martinez, *in* Martinez and others, 1975), there is a strong possibility that ground-water hydrology may have also exerted an influence on the depth to domes throughout the basin. In addition to cap-rock development, most domes have risen sufficiently within the stratigraphic succession to penetrate Tertiary strata.

Netherland, Sewell and Associates (1976b) also indicated that the number of wells drilled within 4 km of several domes in the southern half of the basin is quite variable, ranging from 2 on McLaurin and County Line domes to 48 on Tatum dome. The latter, as reported by Rawson and others (1966) and Eargle (1968), represents the most intensely studied dome in the basin, because of its use in the 1960's for the Salmon Event. The latter involved an underground nuclear detonation and its detection in experiments conducted by the U.S. Atomic Energy Commission and the U.S. Department of Defense, respectively. Because of the scarcity of subsurface data on certain domes, detailed descriptions of the geology, hydrology, cap-rock relations, and structure are simply not possible.

With the possible exception of studies by Netherland, Sewell and Associates (1975a), in which the potential for future petroleum development near several shallower domes was evaluated, and Smith (*in* Martinez and others, 1976), in which the ground-water hydrology of three domes was investigated, no detailed assessment has been made of domes in the Mississippi basin. The earlier work by Eargle (1968) and Anderson and others (1973) thus represents the extent to which domes here have been evaluated outside proprietary industrial studies aimed at exploration for petroleum and other mineral resources.

Hydrology

Surface Water

Surface drainage is southward into the Gulf of Mexico, as the northwestern part of the basin contributes runoff to the Mississippi River and several tributary streams, such as the Yazoo, Big Black, and Tensas Rivers, which feed into the Mississippi River. The central part of the basin drains primarily into the Pearl River system, whereas runoff along the eastern margin enters the Pascagoula River network; both these streams flow into the Gulf of Mexico. Several smaller streams, such as the Homochitta River, Chitto River, and Tallahoma Creek, develop their headwaters within the basin.

Of the annual rainfall, which varies from 130 cm in the northwest to 160 cm in the southeast, most is lost back to the atmosphere or becomes runoff. Some water provides recharge to the ground-water regime. Average annual runoff in southern Mississippi, however, may be as much as 75 cm. By contrast, the ground-water system provides significant discharge from the basin into the Mississippi River alluvial plain (Payne, 1968).

Although several domes are in well-drained uplands, others lie beneath flood plains, areas of poor drainage, or land subject to flooding.

Table 3.-Features of Salt Domes in Mississippi Salt-Dome Basin

Dome Name	Depth to top of salt				Cap rock encountered	Surface saline	Commercial utilization					
	< 300 m	300—1000 m	1000—3000 m	> 3000 m			Salt mine	Brine wells	Oil/gas production on dome	Hydrocarbon storage	Sulfur production	Surface mine
Allen		X			X							
Arm		X			X							
Ashwood (Somerset)			X		X							
Baxterville				X	(X)?							
Brownsville			X		X							
Bruinsburg		X			X		X		X			
Burns				X								
Byrd		X			X							
Carmichael		X			X				X			
Carson		X			X							
Caseyville		X										
Centerville		X			X							
Chaparral (Hiwanee)				X					X			
County Line		X			X							
Crowville				N.D.	X							
Cypress Creek				N.D.	N.D.							
D'Lo		X			X							
Dont		X			X							
Dry Creek		X			X							
Duck Port			X									
Eagle Bend			X		X							
Edwards		X			X							
Ellisville				X	X							
Eminence		X			X							
Eucutta				X	X				X			
Foules			X		X							
Galloway			X		X							
Gilbert		X										
Glass			X		X							
Glazier			X		X				X			
Grange				X					X			
Gwinville				X					X			
Halifax			X		X							
Hazelhurst				N.D.	X							
Heidelberg			X		X				X			
Hervey			X		X							
Kings			X		X				Abn.			
Kola		X			X							
Lampton		X			X							
Laurel				X					X			
Learned			X		X							
Leedo		X			X							
McBride		X			X				X			
McIntosh	X				X			X				
McLaurin		X			X							
Midway		X			X							
Monticello		X			X							
Moselle		X			X							
Newellton			X		X							
New Home		X			X							
Newman			X		X							

Table 3— *Continued*

Dome Name	Depth to top of salt				Cap rock encountered	Surface saline	Commercial utilization					
	< 300 m	300—1000 m	1000—3000 m	> 3000 m			Salt mine	Brine wells	Oil/gas production on dome	Hydrocarbon storage	Sulfur production	Surface mine
North Tallulah (Tallulah)			X		X							
Oakley		X							Abn.			
Oak Ridge			X									
Oakvale		X			X							
Ovett				X					X			
Petal		X			X					LPG		
Prentiss		X			X							
Raleigh		X			X				X			
Richmond		X			X							
Richton	X				X					LPG		
Rufus				X								
Ruth		X			X							
Sardis Church				N.D.	X							
Singer			X		X							
Snake Bayou			X									
South Carleton				X					X			
South Coleman			X									
South Tallulah		X										
Sunrise			X		X							
Tatum		X			X			NTB				
Utica		X			X							
Valley Park				X	X				Abn.			
Vicksburg			X		X							
Walnut Bayou		X			X							
Wesson			X		X							
Yellow Creek				X					X			

N.D., not yet drilled; Abn., abandoned; LPG, liquefied-petroleum-gas storage; (?), presence of feature questionable or disputed; NTB, Nuclear-test blast.

Data from Hawkins and Jirik (1966), Halbouty (1967), Anderson and others (1973), Martinez and others (1975, 1976), Netherland, Sewell and Associates (1976a).

Ground Water

Fresh ground water represents a prolifically abundant and valuable, although underdeveloped, resource within the Mississippi basin and ranges from less than 120 m to more than 750 m below the land surface. Useful studies about this resource include several reports issued by the Mississippi Research and Development Center in Jackson, Mississippi, as part of that group's assessment of water availability for industrial development within the state. Shows (1970) also discussed ground water in his treatment of the state's water resources, while Newcome (1967) and Lang (1972) considered the ground-water regime within the Pascagoula and Pearl River drainage areas, respectively. One of the basin's principal aquifers, the Eocene Sparta Sand, was also studied by Payne (1968) on a regional basis.

In addition to the Sparta Sand, important bedrock aquifers include other sandstone units within the Eocene Claiborne Group, sandstones of the Eocene Wilcox Group, and various undifferentiated, lenticular sands within the Miocene sequence. Alluvial deposits of the Mississippi River valley also yield fresh water in the western part of the basin.

Throughout the region, the base of fresh ground water slopes essentially toward the southwest, or slightly across the gulfward regional dip of the stratigraphic sequence. Within the eastern half of the basin, this pattern is modified along a north-south direction as the result of two abrupt decreases in the depth to saline water (Anderson and others, 1973). The first of these occurs in Smith County near the northeast margin of the basin, and represents the extent to which aquifers in the Wilcox Group have been flushed by fresh water. The second, more southerly change occurs in Jefferson Davis County, near the center of the basin, and represents the downdip extent of aquifers within the Claiborne Group. Most of the more shallow domes lie south of this second depth change, where the base of fresh water does not extend below the Miocene. The regional pattern is also modified within the western part of the basin, where Payne (1968) showed that the depth to saline water is strongly influenced by the direction of ground-water flow involved in the significant discharge of fresh water from subsurface aquifers into the Mississippi River alluvial valley. Fresh water within the Sparta Sand is also more extensively distributed and at greater depth (>700 m below the land surface) on the Mississippi side of the valley than the Louisiana side. Fresh-water aquifers above several domes are also either highly productive or capable of sustained production (Anderson and others, 1973).

Unlike many salt domes in the Northeast Texas and North Louisiana basins, the domes here lack surface salines or salt springs. This does not, however, conclusively establish hydrologic stability. Although hydrologic stability or salt dissolution were not objectives of the extensive water-well-monitoring program conducted by the U.S. Geological Survey when the Salmon Event was conducted within Tatum dome, data obtained in those investigations and summarized by Anderson and others (1973) have shown that the cap rock at Tatum contained fresh water and was hydrologically connected to several fresh-water aquifers. Vertical flow through the cap rock, whose lower 130 m consists of porous anhydrite sand, to overlying aquifers was also proved. Despite this suggestion of active dissolution, Smith (*in* Martinez and others, 1976), in studying the water quality of aquifers near this dome by means of resistivity analysis of well logs, did not detect saline water in adjacent fresh-water aquifers. Smith also reasoned that, if salt was being actively dissolved, the resulting dense brine might have moved downward into deeper saline aquifers. In the case of Lampton dome, where no brine was found in overlying sands, dissolution may have been prevented by the associated shale sheath or limited by slow-flowing saline water in contact with the salt stock. Inadequate data on the McLaurin dome prevented a thorough assessment, although no anomalous brines were found in the overlying Miocene sands, apparently owing to a thick clay seal above the cap rock.

Because of the relatively limited number of water wells near several domes, and an inadequate knowledge about the configuration of cap rocks and salt flanks, much needs to be learned about the hydrology around domes in this basin. The degree of salt dissolution, other than the evidence furnished by thick, well-developed cap rocks, remains unknown for most domes. Even the apparent hydrologic instability of Tatum dome, for which the most extensive ground-water data exist, can neither be verified or refuted.

Seismic Activity

Most of the Mississippi basin lies within seismic-risk zone 1, where minor earthquake damage can be expected, although the southeastern part extends into seismic-risk zone 0, which is characterized by no reasonable expectancy of earthquake damage (see fig. 16). According to data from Coffman and von Hake (1973), no seismic events having intensities of MM V or greater have ever been recorded within the basin proper. One earthquake of intensity MM V occurred in 1955 along the Mississippi coastline south of the basin's south boundary, whereas two events were recorded in 1967 near Greenville, Mississippi, or to the north of the basin. The larger events registered an intensity of MM VI over a felt area of 65,000 sq. km.

To the north lies the more seismically active trend known as the New Madrid zone. Although the center of this zone, best known for several large events (estimated Richter magnitude of 8 or greater) that occurred in the early 1800's, is located where Missouri, Illinois, and Kentucky join, the sphere of influence extends southward to the point where Louisiana, Arkansas, and Mississippi meet at a common point. As shown in figure 16, this extension is delineated by seismic-risk zone 2, where moderate damage can be expected. One event of intensity MM VII was recorded in eastern Arkansas near the Mississippi-Tennessee state line, and a number of other events displaying intensities above MM V have been recorded here as well (see fig. 15). Although felt areas from the earthquakes within the New Madrid zone might extend into the Mississippi basin, there is no evidence at hand to suggest that any damage, especially in the subsurface, resulted from these more northerly seismic events.

Likewise, there is no evidence to indicate that any measure of seismicity has ever been recorded adjacent to a salt dome within this basin. Based upon these considerations, any hazards from seismic activity in this basin would appear to be minimal.

Mineral Resources

Oil and Gas

Of the 77 known and suspected salt domes in the Mississippi basin, only 11 domes—Chaparral (or Hiwanee), Eucutta, Glazier, Grange, Gwinville, Heidelberg, Laurel, Ovett, Raleigh, South Carleton in Alabama, and Yellow Creek—have any significant petroleum production associated with them (Halbouty, 1967; Beebe, 1968). Of these, only Raleigh dome is less than 1,000 m in depth; the others are all deeper than 2,500 m, or too deep for current consideration. Small producing fields associated with Kings, Oakley, and Valley Park domes were of little significance and are now abandoned. McBride and Bruinsburg domes also have small shut-in gas fields associated with them. Even if the domes here are not especially productive, structures related to the deep flowage of salt are the most important traps in the Mississippi basin (Beebe, 1968).

Work by Netherland, Sewell and Associates (1975a) indicated that nearby production had also been developed adjacent to Lampton and Tatum domes (of the 10 domes studied by them), and in these cases the nearest field was at least 5 km distant. As cited by these investigators, the paucity of hydrocarbons around domes here may be explained by one of three mechanisms: (1) the petroleum migrated past the domes before the domes could provide traps; (2) the surrounding rim synclines blocked petroleum from migrating to the domes; or (3) post-diapiric faulting and movement allowed any entrapped petroleum to escape. In their opinion, too, adequate test wells have been drilled to confirm the low hydrocarbon potential near many of the domes in this basin.

Within the basin, but outside the northwest-aligned belt of generally shallower domes, there are two productive trends of significance. Along the northeast and eastern margins, deep production has been obtained from the Smackover and other Jurassic intervals, while to the southwest, production has come primarily from Tertiary units such as the Wilcox Group. Drilling to expand these trends can be expected within interdomal areas but not directly above domes. Interest since 1974 in the Lower Cretaceous Hosston Formation has also led to deep drilling near the center of the shallow-dome trend (Cate, 1977).

Salt

Despite the large number of salt domes here, only two have been developed for the production of salt. The very shallow McIntosh dome in Alabama sustains a brining operation, whereas a productive rock-salt mine has recently been developed in Bruinsburg dome. This seemingly low level of development may in part reflect the greater average depth of the domes in this basin. Likewise, only two domes, Petal and Richton, have been utilized for the cavern storage of LPG.

Although salt mining may have temporarily eliminated one possibly favorable dome (Bruinsburg), significant volumes of salt remain in other domes for future recovery. An increase in salt mining in the domes here also seems unlikely. In the event that a dome in this basin were proved to be acceptable for waste storage, the salt-resource base or storage potential of this basin would not be adversely affected.

Sulfur

Even though cap rock has formed on most of the salt domes here and has attained considerable thickness in several cases, none has produced native sulfur, and exploratory drilling specifically for sulfur has not revealed any promising mineralization. Based upon the currently available information, sulfur mining does not pose any future competition.

Other Minerals

Mississippi is an important producer of bentonite and fuller's earth, clays that find many industrial-mineral applications. Although most of the production comes from counties in northeast Mississippi, one bentonite operation is located to the northeast of the zone of more southern domes. Common brick clay is also recovered from surface pits near various domes, while sand and gravel are locally mined in several other counties within the salt-dome basin. Limestone for the manufacture of portland cement is also quarried at one site.

None of these surface-mining activities presents either a competitive situation or a hazard to any salt dome shallow enough to warrant further detailed evaluation.

Regional Evaluation for Storage of Radioactive Waste

There are 77 known and inferred salt domes in this basin, but the depth to the top of salt in 36 of them exceeds the optimum depth range of 300 to 1,000 m. Salt also has not been encountered by drilling in four other domes. Of the 37 remaining domes, 3 support current and sizable production of petroleum, 2 are utilized for LPG storage, 1 is utilized for the production of brine, and 1 contains a producing rock-salt mine. In none of the remaining 30 domes is the top of the salt shallower than 300 m, and in most the salt is deeper than 600 m. Thus, although there are domes which are neither excessive in depth nor preempted by industrial activity, they tend to be generally deeper than in the other interior basins.

Although a significant amount of geologic and hydrologic data was acquired on Tatum dome here, the converse is the case for most other domes; i.e., either little information is known and/or available, or few wells have been drilled sufficiently close to provide useful subsurface data. Relatively little is known about the ground-water hydrology adjacent to most of these domes, and where a few domes have been studied in more detail, results from the evaluation of the hydrologic stability have been inconclusive.

Although this basin lies closer to a seismically active belt than the other Gulf Coast basins, it is sufficiently removed geographically that seismic events to the north should not be of concern here.

Inasmuch as many domes are located at remote, well-drained sites, and competition from conflicting developments such as mineral recovery and hydrocarbon storage appears minimal, these domes exhibit a definite measure of potential, provided their generally greater depth is not a deterrent. Clear, however, is the need to acquire additional data from geophysical surveys, water wells, and deeper test boreholes before the more promising domes can be fully evaluated.

TEXAS-LOUISIANA COAST SALT-DOME BASIN

Structure and Geologic Framework

Inasmuch as many of the stratigraphic, depositional, and structural features developed here are typical of the regional Gulf Coast basin, a more limited discussion on this dome-bearing basin is presented here. Although sedimentation in this basin began in the Jurassic and persisted into the Cretaceous, the now deeply buried sequences formed then comprise a much smaller part of the stratigraphic succession in comparison to the thick overlying Tertiary intervals. Since Jurassic times, the depositional axis of this basin has shifted gulfward, and, moreover, since Early Tertiary time, the center of maximum deposition has moved eastward from the Houston embayment area of south Texas into south Louisiana.

Outcrops of Tertiary strata are largely nonexistent owing to a masking by Quaternary- and Holocene-age alluvial and coastal-terrace deposits, except near certain inland salt domes, such as Hockley and Davis Hill domes, where uplifting has exposed normally buried units. Despite this, the subsurface stratigraphy is well known, based on samples and cores from numerous exploratory petroleum tests, mechanical logs run in these wells, geophysics, and paleontologic zonation largely from abundant and commonly distinctive foraminiferal assemblages. In a general sense, all the Tertiary sequences thin in a landward direction and are represented by a more continental phase of the formative deltaic depositional system. Marine facies may, however, extend into these continental-deltaic units. The same intervals that thin in an updip direction, unless faulted upward or uplifted by salt domes, lie at increasingly greater depths toward the gulf.

Also, the stratigraphic units not only thicken gulfward but develop a more marine character and commonly become much more enriched in shales and clays. Through time, there has also been a generalized, gulfward displacement of the inner shelf or neritic facies, which is the most prospective for petroleum in each of the Tertiary series. Of course, depositional facies changes, growth faults and their control on sedimentation, salt diapirs, and effects from salt flowage have created much more complex geology than is typically realized by many geologists not familiar with this region. Where good marker beds are available on the mechanical logs and can be combined with paleontological evidence, regional correlations are reasonably accurate. Efforts to correlate deeper subsurface units with formations exposed at the surface inland are, however, complicated by an absence of marker foraminifers in the more sandy, updip continental facies; this makes subdivision of the sequence very difficult. Expanded sections on the downthrown side of growth faults and irregular turbidite deposition further compound the problem of correlation.

Salt domes near the Gulf of Mexico in both Texas and Louisiana are related to a stratigraphic sequence more typical of the Gulf Coast basin in general, as discussed in detail by the Lafayette and New Orleans Geological Societies (1968) and Shinn (1971). Because of the reliance of foraminiferal zonation and a stratigraphic terminology that is nearly all subsurface in nature, no further discussion is presented here. Those domes that lie farther inland in Texas are, however, associated with a sedimentary sequence that is more similar to those applicable to the Northeast Texas and South Texas basins (figs. 31, 36).

Additional articles that summarize existing information on the stratigraphy and subsurface geology of this region include Murray (1961), Lofton and Adams (1971), and Tipsword and others (1971). Many specific citations from the abundant petroleum-related literature can also be found in the references compiled by Braunstein (1970) and in Cram (1971).

Salt Domes

Even if offshore domes are excluded, the Texas-Louisiana coast basin contains more salt domes than the other four basins combined. Of the 143 known domes in this basin, more than half, or 73, sustain an appreciable level of competitive industrial activities. The latter currently involve production of petroleum, mechanical mining of salt, production of brines and sulfur, storage of LPG and crude oil, or a combination of these. Another 66 domes are viewed as being too deep for practical consideration at this time; i.e., the top of salt is deeper than 1,000 m. Of the four remaining domes, none occurs within the Louisiana portion of the basin. Three of the Texas domes, exclusive of Davis Hill dome northeast of Houston, lie west of a north-south line drawn through Galveston Bay. Characteristics of these three domes include shallow depth, thick and well-developed cap rocks, and subsurface penetration above the regional level of fresh water. The top of salt in them all is shallower than 360 m, while the salt in Hawkinsville dome is as shallow as 135 m. Cap-rock thickness varies from slightly more than 80 m in Gulf dome to 160 m in Hoskins Mound dome.

Gulf, Hawkinsville, and Hoskins Mound domes lie along the low, marshy coastal plain adjacent to the Gulf of Mexico. All thus lie within a few kilometers of a coastline that is typified periodically by strong tropical storms whose large tidal surges and high rainfall create pronounced flooding in this part of Texas. Even though Gulf dome underlies a hill that rises 9 m above the general terrain, the low adjacent areas, once flooded, would preclude access to any facility conceivably located in that dome. Proximity to the coast in an area susceptible to flooding and destructive storms significantly reduces the potential of these domes.

Farther inland, Davis Hill dome supports a 45-m hill, around which uplifted Miocene and Oligocene strata are exposed over a broad area. Minor oil production is now shut in, but only two wells have been drilled into the salt. Hawkins and Jirik (1966) estimated that the salt area at a depth of 1,500 m was nearly 15 sq. km, indicative of a sizable salt mass. Inasmuch as the depth to salt here is less than 400 m, the dome is also shallow. Not much is known, however, about the subsurface hydrology around the dome or the hydrologic stability of the salt mass. Despite these limitations, this dome appears to be one whose preliminary potential may warrant some future consideration.

Hydrology

Surface Water

Because the few domes that are either not too deep nor committed to industrial usage are all within the western part of this basin, attention focuses on the hydrology there, or that within the Northeast Texas Coastal Plain. The average annual precipitation in this region varies between 100 and 125 cm from west to east. Hurricanes, however, have been known to cause precipitation of more than 60 cm in one day. Such high levels of concentrated rainfall, when combined with the low-lying, marshy-swampy terrain, create severe flooding. Torrential thunderstorms can also produce less pronounced, local flooding. The problem is most severe along major streams such as the Colorado, Brazos, and Trinity

Rivers, or close to the coastal marshes toward which much of the runoff is directed and behind whose barrier bars water can build up owing to the poor drainage there.

Inland from the coast, small streams drain principally toward the coastal marshes, although many serve as tributaries to the major, through-flowing streams. The latter, especially the Brazos and Trinity, support actively building deltas; sedimentation in this form and from other stream influx continues to fill in the shallow bays and marsh areas behind the barrier bars. This cycle produces additional poorly drained swampy marshland along the coastline. Gulf, Hawkinsville, and Hoskins Mound domes are located in the midst of this kind of hydrology-depositional system and are prone to either surface flooding or isolation because of water inundation of adjacent territory.

Davis Hill dome, which supports a topographic high, appears safe from flooding by the nearby Trinity River. Lower lying land around this dome might, however, remain flooded.

Ground Water

Articles that discuss the regional ground-water conditions in this part of the basin include several publications by the Texas Water Development Board (Anders and others, 1968; Hammond, 1969; Wesselman, 1972), reports by the Texas Water Commission (Wood and others, 1963; Baker, 1964), and the U.S. Geological Survey (Petitt and Winslow, 1957; Winslow and others, 1957).

The principal fresh-water aquifers in the Texas portion of this basin are the Pleistocene Willis Sand and the Pliocene Goliad Sand. These units delineate a band that varies in width from 80 to 150 km and parallels the coast. For much of this trend, fresh ground water extends to the base of the deeper Goliad; as the coast is approached, the base of fresh water rises within these units, reflecting the limit to which they have been flushed in a gulfward direction. Thus, at the coast, these aquifers contain saline water. The depth to the base of fresh water varies along this trend from 480 to 900 m (Anderson and others, 1973).

Along the coast, other younger Pleistocene-age sandy units and Holocene-age deltaic sediments constitute the fresh-water aquifers. These units contain fresh water inland for nearly 100 km but rarely yield fresh water from depths greater than 300 m. The value declines to 180 m near the coast. Locally in the coastal area, fresh water is not found within the subsurface.

Ground-water conditions near the three coastal domes and Davis Hill dome are not known with adequate clarity, and thus specific investigations on the ground-water hydrology around these domes are needed.

Seismic Activity

The onshore portion of this salt-dome basin lies astride seismic-risk zones 1 and 0, where little to no damage can be expected. Most of the latter zone lies within the state of Texas (see fig. 16). Coffman and von Hake (1973) furthermore reported no events above intensity V on the Modified Mercalli Scale for the basin (see fig. 15).

No microseismic monitoring of salt domes in south Louisiana has been reported, although seismograph studies were made of Hockley dome in Texas by a Rice University graduate student (Thoms and Manning, *in* Martinez and others, 1976). The microseismic-monitoring system of Thoms and Manning also utilizes a south Louisiana dome where an active salt mine with known energy inputs (blasting) can be used for calibration. Data from this calibration conceivably could provide useful information on salt domes and their response to seismic events.

As previously stated, salt domes within the Texas-Louisiana coastal basin are felt to be tectonically unstable in comparison to those of the interior basins. The question of whether this inferred tectonic instability is accompanied by microseismic activity (other than that from salt dissolution) or localized seismic energy releases remains to be answered. The generally low level of seismicity, however, seems to indicate that seismic hazards are at a minimum in this basin.

Mineral Resources

Oil and Gas

The Texas-Louisiana coastal basin, especially if the offshore portion is included, represents one of the most prolific petroleum provinces in the United States. Numerous oil fields, each having ultimate recoverable reserves greater than 16 billion liters (100 million barrels) have been found here; gas fields each containing reserves of more than 15 billion cubic m (500 billion cubic feet) of natural gas are also common. In onshore Louisiana alone, there are 30 oil fields of this size (Sandt and Woltz, 1977). Extensive oil and gas production has been established in this basin for more than seven decades, commencing with the famous Spindletop discovery in 1901. Modern offshore exploration and production in this country also began in earnest here in the early 1950's.

The petroleum geology of this basin was discussed by Hanna (1959), Atwater and Forman (1959), Murray (1961), Halbouty (1967), and the Lafayette and New Orleans Geological Societies (1968). Additional references on specific petroleum-bearing dome and non-dome fields are cited in the extensive bibliography by Braunstein (1970).

The significant volumes of hydrocarbons discovered to date are principally found within the thick, clastic-dominated Tertiary sequence. Production has also been established, however, in both Cretaceous and Jurassic strata above the Louann Salt. The Smackover Limestone and Tuscaloosa Sandstone are two productive pre-Tertiary intervals, although the former is better known as a petroleum reservoir farther to the north and northeast. Broad, east-west belts which extend across Louisiana and indicate the general age of the production, become successively younger in a gulfward direction. Thus, Eocene and Oligocene production is found exclusively onshore, Miocene production occurs both onshore and offshore, and Pliocene and Pleistocene production occurs exclusively offshore. In a westward direction into Texas, however, these producing trends develop a southwest alignment and parallel the Texas coastline. Therefore, the onshore extent of the Miocene producing trend is smaller, and Oligocene production extends almost to the coastline. In both states, the older Jurassic and Cretaceous productive belts lie inland of the oldest Tertiary trend. Of course, the establishment of deeper, downdip production may cause overlap between these trends; for example, recent deep gas discoveries in the Tuscaloosa Sandstone northwest of Baton Rouge, Louisiana, lie to the south of the established Cretaceous trend.

Salt domes and salt tectonics have played an important role in providing trapping devices for much of the petroleum generated and accumulated in this basin. Of the 143 onshore domes here, nearly 130 have associated oil and gas production. Some of the region's largest fields have been discovered above or along the flanks of these domes.

Petroleum has accumulated around salt domes in the following specific traps: (1) domed strata above the dome; (2) grabens above the dome; (3) porous cap rock; (4) flanking sands under an overhang, against the dome proper, or where the dome has caused lensing out of the sand bodies; and (5) fault segments above or around the periphery of the dome (Halbouty, 1967). In addition to the direct role of salt domes, salt flowage in the deeper subsurface has produced anticlinal closures in overlying strata. Many of these so-called ''low-relief'' anticlines occur between domes or between clusters of domes. Growth faults in which strata on either block can be ''rolled over'' into anticlinal closures constitute another highly productive trapping mechanism here. Oil and gas also have accumulated along faults where permeable reservoirs have been displaced against shales, thus preventing further oil migration. Stratigraphic traps involving sand pinchouts and wedgeouts are also important, especially along the Texas Gulf Coast. Thus, salt diapirism, faulting associated with both rapid Tertiary sedimentation and salt-dome growth, and structures caused by deeper salt tectonics have combined to provide numerous traps for the accumulation of oil and gas here.

Salt

Based on statistics compiled annually by the U.S. Bureau of Mines, the states of Texas and Louisiana have accounted for more than one-half of the country's production of salt in each year since 1970. With the exception of one dome each in the Northeast Texas and North Louisiana basins, most of the salt has been produced from underground mines and brine fields in several domes within the Texas-Louisiana coastal basin.

Rock-salt mines are currently operated at the following domes in this basin, and by the firms indicated (Hawkins and Jirik, 1966): (1) Avery Island, International Salt Co.; (2) Belle Isle, Cargill, Inc.; (3) Cote Blanche Island, Domtar, Inc.; (4) Hockley, United Salt Corp.; (5) Jefferson Island, Diamond Crystal Salt Co.; (6) Weeks Island, Morton Salt Co. Except for Hockley dome, the other domes constitute the well-known ''five islands'' of south Louisiana. The only other rock-salt mines within the Gulf Coast are at Winnfield dome (now flooded) in the North Louisiana basin, Grand Saline dome in the Northeast Texas basin, and Bruinsburg dome in the Mississippi basin.

Also important is the salt recovered as artificial brines from several domes in this basin. Both salt companies and chemical firms that process the brines for chlorine operate brine fields. Brines as discussed here excludes those produced during the development of caverns for the subsurface storage of hydrocarbons; these brines are generally injected into nearby saline aquifers as a means of disposal. Domes here that currently support brining operations include Anse la Butte, Barbers Hill, Bayou Choctaw, Blue Ridge, Bryan Mound, Chacahoula, Darrow, Napoleonville, Pierce Junction, Sorrento, Stacks, Stratton Ridge, Sulphur Mines, and West Hackberry (Hawkins and Jirik, 1966; Halbouty, 1967; Anderson and others, 1973). Exclusive of Cote Blanche Island dome, the other four ''five-island'' domes also support brining operations in addition to the rock-salt mines located in each (Hawkins and Jirik, 1966).

Gulf Coast salt domes utilizing caverns developed by solution mining are also extensively used for the storage of LPG (liquefied petroleum gases). This petroleum-related application has been developed in some 14 domes in this basin to date (Anderson and others, 1973), and other projects conceivably will be installed in the future. In a similar application, caverns in domes are now being used to store crude oil as part of the federal government's strategic storage program (Allen, 1976). Three domes in this basin—Bayou Choctaw, Bryan Mound, and West Hackberry—have been designated as the first storage sites. Several other domes are contemplated for additional solution-cavern facilities (Craven and Tolbert, 1976), while salt mines in three domes (Cote Blanche, Grand Saline, and Weeks Island) are also being considered (Allen, 1976).

The large number of domes judged suitable for LPG facilities, crude-oil storage, and salt recovery make it unlikely that the possible use of one dome for radioactive-waste storage would compromise either the petroleum-storage program or the salt industry in this region.

Sulfur

The Gulf Coast region is well known for its significant production of native sulfur from the cap rocks of salt domes by means of the Frasch process. Excluding 3 productive domes in the offshore, a total of 25 domes have produced, or are producing now, sulfur from cavernous cap rock. Only one of these domes, Palangana, lies outside of the Texas-Louisiana coastal basin.

At present, production is obtained from the following onshore domes: Boling, Bully Camp, Fannett, Garden Island Bay, Lake Pelto, Lake Washington (or Grand Ecaille), Long Point, Moss Bluff, and Spindletop (Gittinger, 1975). Now-abandoned facilities at Gulf and Hoskins Mound domes were operated respectively by the Texas Gulf Co. and the Freeport Minerals Co. Production at the former dome ended initially in 1936, although a second operation extended from 1965 to 1970, at which time the facility was dismantled and removed. Hoskins Mound dome was productive from 1923 until 1955. No sulfur has been discovered at Davis Hill dome, and that detected at Hawkinsville dome appears to be noncommercial.

Future recovery of sulfur would not appear to be a limiting factor in regard to those domes that lacked past production. Current economics in the sulfur market also argue against a reopening of the abandoned facilities at Hoskins Mound dome, even though some reserves remain.

One question that requires study is the degree to which Frasch mining has affected the cap rock and underlying salt mass on these domes. Subsidence and possible dissolution of salt by excess water represent topics of concern that need to be addressed.

Other Minerals

Other mineral resources recovered now or in the past within the Texas-Louisiana coastal basin include (1) sand and gravel, (2) clays, (3) oyster shells (for lime and limestone uses), (4) limestone, and (5) gypsum. Mining for all these resources has been exclusively by surface methods, including dredging. None of the resulting surface pits, however, pose a future hazard to any dome.

Limestone and gypsum that have been produced from the exposed cap rocks of certain domes here are no longer being mined. Limestone came from Pine Prairie dome; gypsum came from Hockley dome.

In summary, the present and/or future recovery of other mineral resources within this basin does not appear to constitute an adverse situation.

Regional Evaluation for Storage of Radioactive Waste

Despite the presence of the largest number of salt domes within any Gulf Coast basin, this basin contains only four domes that currently appear to be potential candidates for future consideration and additional study. Of the 139 domes here that seem to lack appreciable promise, 66 are at depths greater than the optimum range of 300 to 1,000 m. The remaining 73 domes support a varied array of industrial applications, especially the production of oil and gas. Many domes also support more than one use, and thus there are many areas here where the concentration of industrial activities involving salt domes becomes pronounced.

Although the depth to salt in Hoskins Mound, Hawkinsville, and Gulf domes is favorable by being less than 400 m, these domes are close to the Gulf of Mexico along a topographically low, marshy coastal area that is prone to periodic flooding and the ravages of hurricanes. Possible flooding of land above any dome, or the restriction of access to any dome owing to the prolonged flooding of nearby land, understandably reduces the potential even if subsurface conditions appear promising.

Davis Hill dome thus is the only dome here that is both shallow and lacks industrial development, and is sufficiently inland so that flooding typical of the coastline is not a problem. This dome supports a topographically high area, but its proximity (4 km) to the Trinity River would require evaluation. Periodicity of stream flooding and the extent of such flooding to low-lying, adjacent terrain would be especially needed information. Little, however, is known about the ground-water hydrology adjacent to the dome, or whether dissolution of the salt mass is under way presently or not.

In addition, no study has been made to date on the growth histories of any of these domes. Information about past tectonic development, including Holocene events, would be needed to provide answers about overall tectonic stability.

The sizable number of deep domes within this basin, the high level of concentrated industrial activity on many other domes, and the yet-unanswered question about current-day uplift in these domes collectively tend to reduce interest markedly in this basin. Additional geologic and hydrologic studies are furthermore mandated on the four domes that are neither too deep nor already committed to industrial purposes.

SOUTH TEXAS SALT-DOME BASIN

Structure and Geologic Framework

The triangular-shaped South Texas salt-dome basin forms the more gulfward portion of the larger, southeastward-plunging Rio Grande synclinal basin (or embayment) in southeasternmost Texas. Although the Rio Grande embayment contains exposed older Tertiary and Cretaceous rocks along the southwest margin, outcropping units within the South Texas basin range from middle Eocene strata on the west to Pleistocene and Holocene deposits along the east margin. The latter include coastal terraces at the western ends of Corpus Christi and Baffin Bays and sand dunes and deltaic sediments of the Rio Grande River to the north of the river. A nearly flat plain that slopes toward the gulf at only 1 m per 2.5 km has formed on these younger sediments; inland some 80 km, a more mature, rolling topography, developed on the older Tertiary sequence, extends from that point to the west border of the basin.

Within the basin, a largely Tertiary stratigraphic sequence is characterized by alternating marine and nonmarine deposits that display appreciable facies changes and significant variations in thickness. Many intervals are wedge or lens shaped on a regional basis. The strike of these sedimentary units parallels the Gulf of Mexico shoreline; most units thicken gulfward. In the subsurface, the Tertiary section involved within the area of salt diapirs varies in thickness from 1,700 to 2,000 m and is dominated by clastic lithologies (fig. 36). The latter are principally sands, sandstones, and clays. Tuffaceous material and bentonitic (montmorillonitic) clays are common throughout the Eocene, Oligocene, and older Miocene units; the Miocene-age Catahoula Tuff consists largely of volcanic debris.

Even though the stratigraphic sequence has been penetrated by a limited number of salt diapirs within a small geographic area, the parent Louann Salt is thought to underlie a much larger area throughout the basin. Despite this aspect, the South Texas basin is the smaller of the coastal basins, and the area underlain by salt is likewise more limited. No salt deposits or salt structures are furthermore known to the northeast along the adjacent San Marcos arch, which separates this more isolated basin from the western extent of the Texas-Louisiana coastal basin (Halbouty, 1967).

Basin downsinking here was accompanied by the development of faults whose alignment roughly parallels the strike of the formations. Along the northwest border of the Rio Grande syncline, strata are affected by high-angle faults of the Luling fault zone. Displacements up to 150 m are common here, and most downthrown blocks are on the northwest side (Weeks, 1945). To the southeast, but still bordering the South Texas basin along the northwest, are a series of graben structures known as the Charlotte and Fashing fault zones. Downthrown blocks here lie either to the northwest or southeast. Although these two zones actually lie outside the salt-dome basin itself, Anderson and others (1973) believed salt flowage in the deep subsurface assisted and/or caused this faulting. Within the basin proper, the stratigraphic sequence is cut by two principal fault systems, both of which extend considerable distances to the northeast and parallel the regional strike of the sedimentary units. Faults within these systems are principally downthrown to the southeast. Although Weeks (1945) originally projected the Mexia fault zone as far southwest as Duval County, current thinking is that the more westerly Wilcox fault zone (= Mirando-Provident City fault zone to the northeast) and the Vicksburg (or Sam Fordyce-Vanderbilt) fault zone to the east represent independent fault systems. Many of the faults within these two zones formed contemporaneously with Tertiary sedimentation and acted as growth faults in which individual stratigraphic sequences on the

SERIES	GROUP	FORMATION	LITHOLOGIES
PLIOCENE	CITRONELLE	GOLIAD SAND	poorly consolidated sands; minor clay; upper part calichefied near surface
MIOCENE	FLEMING	FLEMING	claystone with less abundant sandstone; Lagarto Clay member recognized locally and in surface exposures
		OAKVILLE SANDSTONE	sandstone; local conglomeratic zones; some consider Oakville and Lagarto as formations
		CATAHOULA TUFF	upper member (Chusa Tuff) is bentonitic claystone and tuff with basal conglomerate; middle member (Soledad) is volcanic conglomerate; lower member (Fant Tuff) is bentonitic tuff; minor sandstone
MIOCENE OR OLIGOCENE (?)		ANAHUAC	subsurface unit; downdip is all shale; updip is interbedded sands and shale
		FRIO CLAY	bentonitic-tuffaceous clay; sands locally abundant
OLIGOCENE	VICKSBURG	undifferentiated	marine shale to north; brackish-water shales and sands to south
EOCENE	JACKSON	WHITSETT	alternating sandstone members (Calliham or Tordilla, Deweesville and Dilworth) and tuffaceous-bentonitic clay members (Fashing, Dubose, Conquista); local fossil zones and lignite
	CLAIBORNE	YEGUA	clay; minor sandstone and fossil zones
		LAREDO	fossiliferous sandstones and interbedded clays

Figure 36. Generalized Tertiary stratigraphic sequence in South Texas salt-dome basin (after Corpus Christi Geological Society, 1968; Anderson and others, 1973; Eargle and others, 1975).

downthrown (gulfward) side became considerably thicker. Several oil and gas fields are also associated with these faults, and nearby uranium deposits may be genetically related to them as well (Eargle and others, 1975).

Salt Domes

The South Texas basin contains only six salt domes: Dilworth Ranch, Gyp Hill, Moca, Palangana, Piedras Pintas, and Pescadito. The latter is unique, because it represents the largest known salt dome in the country. It is also one of the deepest in that the top of salt lies below 4,300 m. The salt in both Moca and Dilworth Ranch domes lies below 1,900 m and is thus also too deep for development, even by current considerations. Piedras Pintas and Palangana domes have undergone industrial usage; the former has appreciable petroleum production associated with it, while the latter is utilized for the production of brine.

Gyp Hill dome, so named because it underlies a small hill supported by the exposed gypsum-bearing cap rock, represents the only shallow dome that does not support industrial activity. The top of salt, as measured by one well, occurs at a depth of 250 m, but other wells have penetrated more than 300 m of cap rock without reaching salt. Halbouty (1967) listed the depth to salt as 350 m. Of some 45 wells drilled within 2 km of the dome, only 2 have encountered salt (Anderson and others, 1973). The dome penetrates a stratigraphic sequence that, above 2,000 m, ranges from the Frio Clay to the Goliad Sand; surficial deposits overlying the Goliad are Pleistocene and Holocene in age. Strata above the dome are radially and tangentially faulted; one such fault block contains a small oil and gas field that produces from units within the Frio.

The Gyp Hill, Palangana, and Piedras Pintas domes have developed cap rock; that in Gyp Hill is exposed at the land surface. The cap rock at Gyp Hill dome is also the thickest developed within this basin.

Hydrology

Surface Water

The climate in southeasternmost Texas is semiarid, with an average annual precipitation of only 57 cm. Individual tropical storms (hurricanes), however, have been known to produce torrential rainfall that equals or exceeds this annual rate. When such events occur, flooding is extensive and long in duration. Topographically high areas, such as the hill underlain by Gyp Hill dome, may escape flooding but remain isolated for long periods of time owing to widespread flooding in adjacent low-lying areas. This tends to reduce the useful potential of this dome significantly.

To the west of the Pleistocene and Holocene sediments is the Bordas Plain, which is underlain by the Goliad Sand. This more deeply eroded surface is drained perpendicularly to its extent, so that runoff enters small, intermittent tributaries to the northeast-flowing Nueces River or the southeast-flowing Rio Grande River. Both these through-flowing streams have developed deltas at the coast. Within the eastern part of the basin, drainage is into sand-filled valleys whose small, intermittent streams carry little water and flow southeast into bays and lagoons along the coastline.

A shallow, brackish-water lake called Laguna Salada is located near Gyp Hill dome. Although this body of water, which occupies an east-west linear depression, lacks a permanent surface outlet, it is connected to a westward extension of Baffin Bay by an intermittent stream (Palo Blanco Creek) that flows during periods of high rainfall.

Ground Water

Because of the low rainfall and intermittent surface drainage, ground water represents a vital resource for municipal and agricultural purposes in this region. Although much of the surficial material is sandy, thus facilitating appreciable infiltration, very shallow aquifers are unreliable because zones of caliche prevent any significant downward movement, and much of the infiltrated water eventually evaporates. Farther to the west, however, infiltration is more pronounced where several bedrock aquifers are exposed at the surface and thus are susceptible to significant recharge. Water entering at this point flows eastward under artesian pressure at rates dependent upon the amount of rainfall, and hence the rate of recharge. Some good-quality ground water is also obtainable from Pleistocene sand deposits nearer the coast.

The principal ground-water aquifer in the area is the Pliocene Goliad Sand, which is highly permeable and contains good-quality fresh water, even though in certain localities saline water has been found in overlying units. In the vicinity of Gyp Hill dome, water for local use is obtained from this aquifer. Fresh water typically exists to depths as great as 750 m in the southeastern part of the basin. To the east of Gyp Hill dome, slightly saline water occurs as shallow as 300 m, while at the dome proper, fresh water does not occur below 90 m. More hydrologic data need to be acquired in order to evaluate fully the hydrology around this dome and the nature of dome stability with regard to the ground-water system.

Seismic Activity

The entire South Texas basin lies within zone 0 (no reasonable expectancy of earthquake damage) on the seismic-risk map (see fig. 16) prepared by S. T. Algermissen (ESSA/Coast and Geodetic Survey, 1969). No earthquakes of MM Intensity V or above have ever been recorded in or near the basin (Coffman and von Hake, 1973). The nearest concentration of events (two of MM V and one of MM VII) is far to the northeast near the Northeast Texas basin (see fig. 15).

Thus, the South Texas basin appears to be significantly free of any hazards associated with seismic activity.

Mineral Resources

Oil and Gas

Petroleum is produced from a number of fields within both the South Texas basin and outlying portions of the larger Rio Grande syncline. Although production has been attained to the northwest of the basin from the Lower Cretaceous Edwards Limestone in association with the regional Luling-Mexia-Talco fault zones (Halbouty, 1968) and from fracture-porosity reservoirs within the Upper Cretaceous Austin Chalk (Scott, 1977), the principal productive reservoirs within the basin are sandstones of the Eocene Wilcox Group, the Oligocene Vicksburg Group, and the Miocene-Oligocene(?) Frio Formation (Halbouty, 1968). Production from the Miocene section, known collectively as the Fleming Group because subsurface separation of the several surface-mapped formations is difficult, has been established to the northeast near the San Marcos arch (Corpus Christi Geological Society, 1968). Natural gas has also been produced from Miocene units from fields in extreme southeast Texas (Halbouty, 1968). Hydrocarbons have also been produced in varying amounts from the six domes in this basin. Production has been most significant on Moca and Piedras Pintas domes, but production has been abandoned on Dilworth Ranch, Palangana, and Pescadito domes.

Principal hydrocarbon-bearing traps within this region involve anticlinal closures on either block of down-to-the-gulf faults and domal closures caused by deeper salt flowage. Anticlinal folds, stratigraphic traps caused by lateral facies changes into shale, and up-to-the-coast faults represent additional trapping conditions (Corpus Christi Geological Society, 1968).

Of the numerous oil and gas fields found to date, the following represent the more significant in terms of ultimate recovery: Agua Dulce, Viboras, Stratton, Borregos, Seelingson, and La Gloria (Halbouty, 1968). Many of the fields in the basin are important for their natural gas. Current exploration and development activity remains high in the South Texas basin, with objectives in the Frio and Wilcox trends receiving the most interest (Klatt and Wells, 1977).

Possibly the most significant oil and gas field in the present context is the La Gloria anticlinal closure, which is developed along the downthrown side of the Vicksburg or Sam Fordyce–Vanderbilt fault system. This major field lies only 11 km northwest of Gyp Hill dome, and it may be related to salt flowage at depth (Corpus Christi Geological Society, 1968). Production here is from multiple sand reservoirs within the Frio Formation.

No assessment of the potential producing trends that extend through the area of salt domes has been made. Although the potential for future hydrocarbon discoveries within this basin remains favorable, the relatively small production from 4 of the 6 domes here suggests that these features will not be prime exploration targets.

Sulfur

Of the significant volumes of native sulfur recovered via the Frasch process from the cap rocks of Gulf Coast salt domes, very little has come from this basin. According to Halbouty (1967), only 237,000 metric tons of sulfur was produced at the Palangana dome during the interval 1928-35. This operation has been abandoned since that date.

Sulfur has not been detected at the two other domes—Gyp Hill and Piedras Pintas—known to have cap rocks. A sufficient number of wells have been drilled into the Gyp Hill cap rock; the possibility of undiscovered sulfur there is considered low.

Salt

None of the domes in this basin contain underground rock-salt mines. The Pittsburgh Plate Glass Co., however, operates a brine field whose wells produce from Palangana dome (Hofrichter, 1968).

The appreciable depth to three other domes here probably precludes their development as salt-producing deposits. The only dome shallow enough to warrant salt recovery is Gyp Hill dome; at present, no considerations along this line are being contemplated. The apparent high degree of irregularity to the salt surface of this dome may have contributed to a lower level of interest, although other factors are undoubtedly involved.

Other Minerals

Although potash mineralization was detected in Palangana dome and evaluated by some 25 test boreholes (Hofrichter, 1968), no commercial production has yet been established. Similar mineralization has not been reported, however, from the other domes in this basin.

A small amount of gypsum was produced in the past from the exposed gypsiferous cap rock above Gyp Hill dome. The open-pit mine there has been abandoned, and any future production appears most unlikely.

Above Palangana dome, an unoxidized deposit of uranium mineralization occurs within the Goliad Sand (Hofrichter, 1968). This uranium deposit is now undergoing pilot testing by the Union Carbide Corp. relative to *in-situ* recovery. Also of significance are the several productive uranium deposits within the Eocene Whitsett Formation throughout Karnes and Live Oak Counties northeast of the salt-dome basin (Eargle and others, 1975). This mineral belt contains several open-pit mines as well as the first *in-situ* recovery operation (Engineering and Mining Journal, 1975). Additional *in-situ* recovery projects have been developed farther to the southwest from this initial facility in Live Oak County, or closer to the salt domes in this basin (Engineering and Mining Journal, 1977). Such development indicates that this low-grade uranium district may ultimately extend across this basin along the subsurface trend of the Oakville Sandstone, which is the principal ore horizon. Whether uranium mining could pose a conflicting utilization of surface acreage here remains to be seen.

Sand and gravel are locally recovered, especially along the coast, but development of this surficial resource presents no competitive or hazardous conflict.

Regional Evaluation for Storage of Radioactive Waste

Based upon an examination of the data available on this basin, only Gyp Hill dome appears to have much potential for further evaluation relative to the storage of radioactive wastes. Three other domes—Dilworth Ranch, Moca, and Pescadito—are greater than 1,900 m deep, and Palangana dome is presently utilized for the production of brine but may soon have a uranium mine developed within strata overlying it. A sixth dome, Piedras Pintas, although it has productive hydrocarbon reservoirs associated with it, is shallow enough (400 m) to possibly receive some future consideration.

The presence of a thick and extensive cap rock above Gyp Hill dome indicates past dissolution of salt. Although fresh-water aquifers that occur at depths less than 100 m near the dome may suggest a current absence of active dissolution, this condition remains to be proved through additional study. A pronounced change in the depth to slightly saline water near the dome could either indicate some present-day dissolution or communication from deeper, saline aquifers whose hydrology has been influenced by the dome's presence.

Little is known about the current tectonic stability of either Gyp Hill or Piedras Pintas dome. Unlike several domes in the Northeast Texas and North Louisiana basins, these domes have not been specifically studied relative to either their growth histories or the presence or absence of indications concerning movement since the Pleistocene.

Special attention must also be given to the proximity of Gyp Hill dome to a coast where hurricanes and large storms are not uncommon. Torrential rainfall and rising tides from such storms have in the past produced extensive flooding, and even though the hill supported by this dome exhibits topographic relief of nearly 20 m, this does not preclude flooding of all surrounding areas and a resulting restriction of access. Because of this possibility of adjacent flooding, the potential of Gyp Hill dome is somewhat lowered.

Although one, and possibly two, domes here warrant further consideration and related study, their potential appears to be less than the more promising domes in the three interior basins.

PERMIAN BASIN

Structure and Geologic Framework

The Permian basin is not a single structural basin but is a large region of the southwestern United States in which Permian-age salts and other evaporites were deposited along with red beds and carbonates. The five principal structural basins in the region are named the Delaware, Midland, Palo Duro, Anadarko, and Dalhart basins (fig. 37). The Permian basin is located in the southwestern part of the tectonically stable interior of North America and is characterized by nearly flat-lying Permian and younger sedimentary rocks that are faulted at only a few places. Strata dip gently into each of the structural basins from adjacent arches and uplifts at a rate of 2 to 10 m per km (0.1° to 0.5°) (fig. 38).

The several structural basins within the broad Permian basin are also the sites of the greatest thickness of sedimentary rock. For example, the Delaware basin has about 8,000 m of sediments overlying the basement, the Midland basin about 5,000 m, the Palo Duro basin about 3,500 m, the Anadarko basin about 12,000 m, and the Dalhart basin about 3,000 m.

Pre-Permian sedimentary rocks in all these basins range in thickness from nearly 1,000 m to as much as 9,000 m and consist mainly of carbonates in the Cambrian through Devonian Systems and fine-grained clastics and carbonates in the Mississippian and Pennsylvanian Systems.

After a long period of tectonic stability throughout the region during most of early and middle Paleozoic time, there was much tectonic activity in the area of the Permian salt basin during Pennsylvanian time. A series of sharp uplifts and arches were created, and adjacent areas subsided to receive thick accumulations of Pennsylvanian and Permian sediments. This period of tectonism was followed by stabilization of the region before the Permian salts were deposited.

During Permian time a broad and shallow inland sea covered much of the southwestern United States, extending northward from west Texas into northwestern Kansas. Because of slow but continual subsidence beneath all parts of this inland sea, a thick sequence of red beds and evaporites (dolomite, gypsum, and salt) was deposited north of the major reefs and other carbonate deposits of the Delaware and Midland basins and the adjacent shelf areas.

Normal-marine water entered the Delaware and Midland basins from the open ocean to the southwest, and after passing over the reefs it entered the shallow inland sea, where evaporation of the water took place. Fresh water from land areas on the east and west mixed with the marine and saline waters; typically, clastic sediments were deposited in the alluvial and nearshore environments, whereas the evaporites were deposited in the more central parts of the inland sea or the deeper parts of the various structural basins.

Permian evaporites in the region formed primarily as a result of evaporation of sea water. The concentration of dissolved solids in the sea water was raised by evaporation until a series of typical evaporite cycles were formed, with carbonate (limestone or dolomite) at the base, overlain by gypsum or anhydrite, and finally by salt. Potash salts were precipitated following halite deposition only in the Salado Formation in the Carlsbad region of southeastern New Mexico and nearby parts of west Texas. The evaporite cycle is represented in some areas by a vertical sequence consisting of (in ascending order) dolomite, gypsum (or anhydrite), and salt. Elsewhere the evaporite cycle is distributed horizontally over large areas; thick sequences of limestone in the south

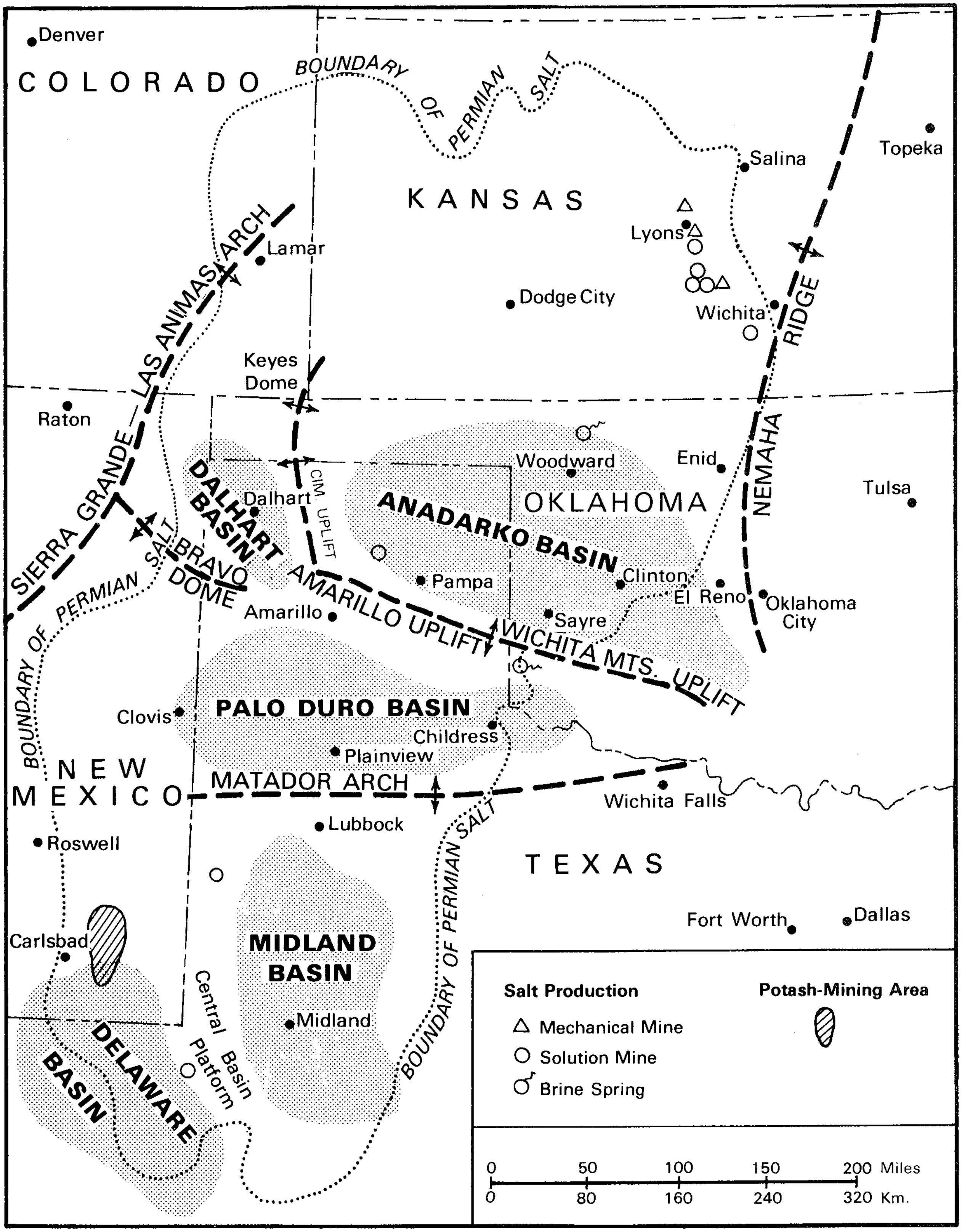


Figure 37. Map of Permian basin salt area in southwestern United States showing principal tectonic provinces.

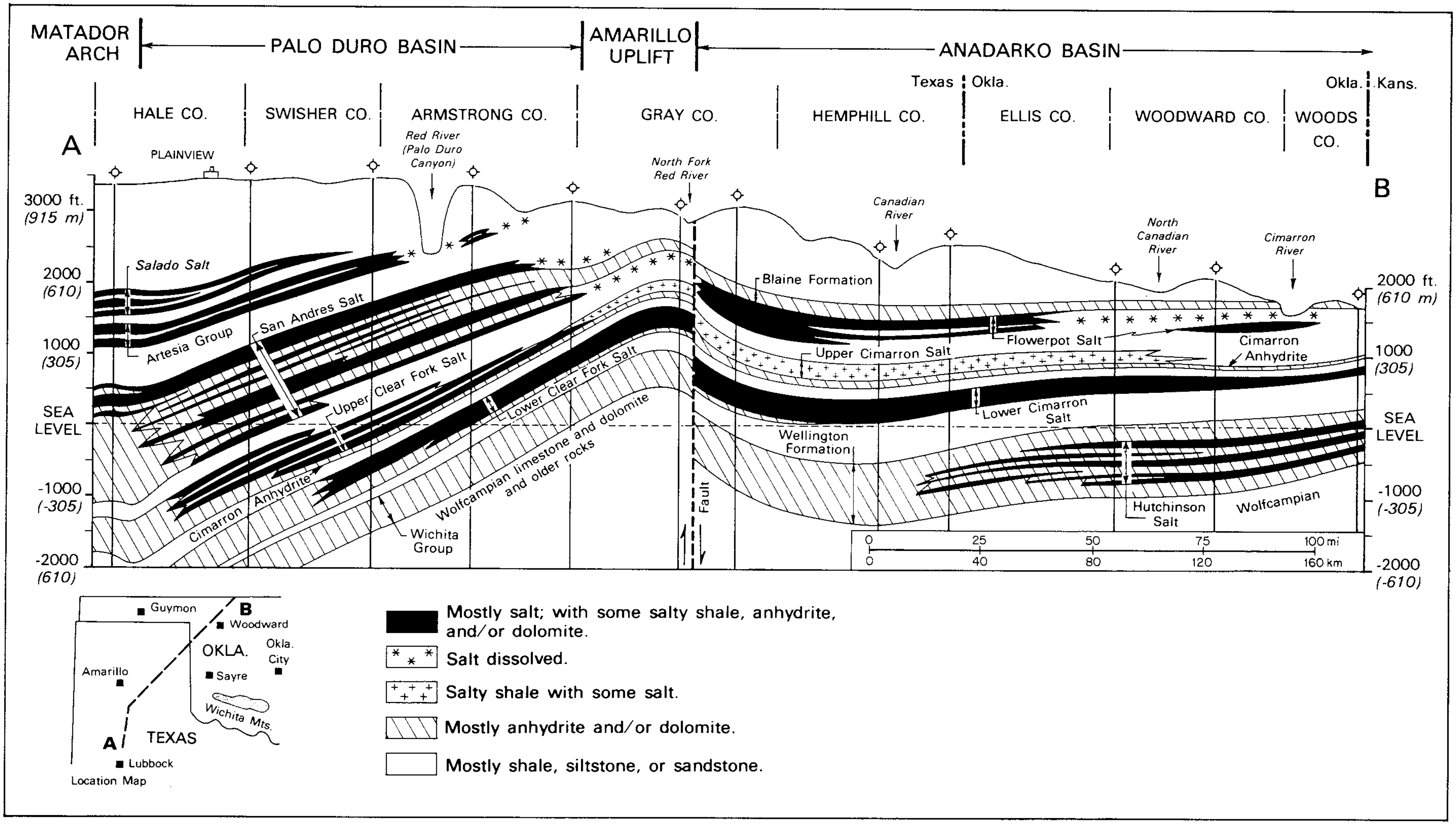


Figure 38. Generalized structural cross section showing Permian salts and associated strata in Texas Panhandle and western Oklahoma (from Johnson, 1976).

grade successively northward into dolomite, gypsum (or anhydrite), and finally, salt.

In addition to the salt that occurs as discrete beds and layers, much of the salt also occurs as isolated and/or intergrown crystals of halite partially surrounded by red shale, siltstone, or sandstone. These large crystals of halite probably developed and grew in the soft sediments either just below the sea bottom or in a supratidal environment shortly after deposition of the encompassing mud, silt, or sand.

Salt deposits are oldest in the northern part of the Permian basin, and they generally are progressively younger toward the south. The site of principal salt deposition was in Kansas and northwestern Oklahoma during early Leonardian time (Hutchinson salt); it shifted into western Oklahoma and the Texas Panhandle during late Leonardian and early Guadalupian time (Lower Clear Fork–Cimarron salt, Upper Clear Fork–Cimarron salt, and San Andres–Blaine salt) and into west Texas and southeastern New Mexico during late Guadalupian and Ochoan time (Artesia, Castile, Salado, and Rustler salts).

Overlying the salts in various parts of the Permian basin are a series of sedimentary rocks and sediments of Permian through Quaternary age. In the northern part of the basin, the salts in Kansas typically are overlain by 50 to 150 m of Permian red-bed shales and sandstones. In western Kansas these are in turn overlain by about 30 m of Jurassic shales of the Morrison Formation and 200 to 400 m of Cretaceous sandstones, shales, limestones, and chalks. This sequence is mantled by the sand, gravel, clay, and caliche beds of the Pliocene Ogallala Formation that commonly is 25 to 100 m thick. The youngest sediments in Kansas are the Quaternary terrace and alluvial deposits of sand, gravel, and clay that are 10 to 30 m thick.

Strata above the salts in the Texas Panhandle–western Oklahoma area include 100 to 300 m of Permian red beds and about 50 to 100 m of Triassic (Dockum Group) and Cretaceous sandstones and shales. These strata are overlain by 25 to 200 m of Ogallala sediments, and locally all the older strata are covered by 10 to 30 m of Quaternary terrace and alluvial deposits.

In west Texas and southeastern New Mexico, the salts are commonly overlain by several hundred meters of Permian red beds of the Rustler and Dewey Lake Formations. These in turn are overlain by 150 to 300 m of Triassic, Jurassic, and Cretaceous sandstones, shales, and limestones, and then by 25 to 100 m of Ogallala or Quaternary sands, gravels, and clays.

The history of the Permian basin has been one of tectonic stability since deposition of the salts. Minor amounts of subsidence have continued in the various structural basins, but the Permian and younger strata are virtually free of deformation and in most areas have dips of less than ½°. The region has not been affected by mountain-building processes, nor has it been covered by the massive glaciers that spread over most of the northern United States.

Faults that displace Permian salt-bearing rocks in the region are rare (Bachman and Johnson, 1973). The Bonita fault in Quay County, New Mexico, displaces rocks of Triassic and Cretaceous age, and presumably it also displaces Permian strata in the subsurface. Permian rocks are locally faulted and sharply flexed along the edges of some uplifts and arches, principally the Wichita-Amarillo uplift and the Matador arch. At other sites, strata overlying the salt sequence are locally disturbed owing to the solution of salt in the shallow subsurface and the attendant collapse of younger rocks.

Igneous activity following salt deposition was limited to southeastern New Mexico (Bachman and Johnson, 1973). Two long dikes are present east of Roswell, and three small dikes are present south of Carlsbad.

Salt Deposits

All the salt deposits in this region are of Permian age. A total of eight principal salt-bearing units are present in different parts of the basin, with the older salts being in the north and the younger salts in the south (fig. 39). The eight salt units are, in ascending order, Hutchinson salt, Lower Clear Fork (Lower Cimarron) salt, Upper Clear Fork (Upper Cimarron) salt, San Andres (Blaine) Formation salt, Artesia Group salt, Castile salt, Salado salt, and Rustler Formation salt.

Salt beds typically have interbeds of shale, anhydrite, limestone, or dolomite and also commonly grade laterally into one or several of these rock types away from the area of salt deposition. Salt-bearing units are commonly 60 to more than 300 m thick, and there are many parts of the Permian basin with thick salts 300 to 900 m below the surface.

Principal sources of information on salt deposits and the geologic framework of the Permian basin are Pierce and Rich (1962), McKee, Oriel, and others (1967a, 1967b), Lefond (1969), and Bachman and Johnson (1973). Data on the Kansas–eastern Colorado part of the basin are found in Kulstad (1959), Jones (1965), Schumaker (1966), Dellwig (1968), Bayne (1972), and Walters (1976). Reports on the Oklahoma–Texas Panhandle–northeastern New Mexico area include Tait and others (1962), Jordan and Vosburg (1963), Johnson (1976), Foster and others (1972), and Jones (1974). Data on west Texas–southeastern New Mexico were discussed by Adams (1963), Brokaw and others (1972), Jones (1974, 1975), and Jones and others (1973).

Hutchinson Salt

The Hutchinson salt, the oldest salt unit in the Permian basin, is restricted to the northern part of the region, in Kansas, Oklahoma, and the northeast corner of the Texas Panhandle (fig. 40). As part of the Wellington Formation, this salt is being, or has been, mined by underground-mining or solution techniques at about 20 sites in south-central Kansas. It was to have been the host rock for the federally proposed radioactive-waste-repository site at Lyons, Kansas.

The Hutchinson salt is typically 60 to 180 m thick and consists of a sequence of interbedded salt, anhydrite, and shale (fig. 41). Salt occurs in individual layers that typically are 2 to 8 m thick in Oklahoma and are apparently much thicker in Kansas. The interbeds of shale and/or anhydrite are commonly 0.3 to 3 m thick. Salt normally represents 40 to 50 percent of the Hutchinson in Oklahoma but represents 60 to more than 80 percent of the unit in much of the Kansas area (Kulstad, 1959). The purity of the salt in salt mines of central Kansas is reported by Lefond (1969) to be 95 to 97 percent NaCl and 2 to 4 percent $CaSO_4$.

The depth to the top of the Hutchinson salt ranges from only about 100 m in central Kansas to about 1,200 m near the axis of the Anadarko basin in western Oklahoma (fig. 40).

Lower Clear Fork (Lower Cimarron) Salt

In the Palo Duro basin and farther south, the name Lower Clear Fork salt is applied to salt strata below the Cimarron Anhydrite and above the Wichita Group. Equivalent strata in the Anadarko basin and farther north are called the Lower Cimarron salt.

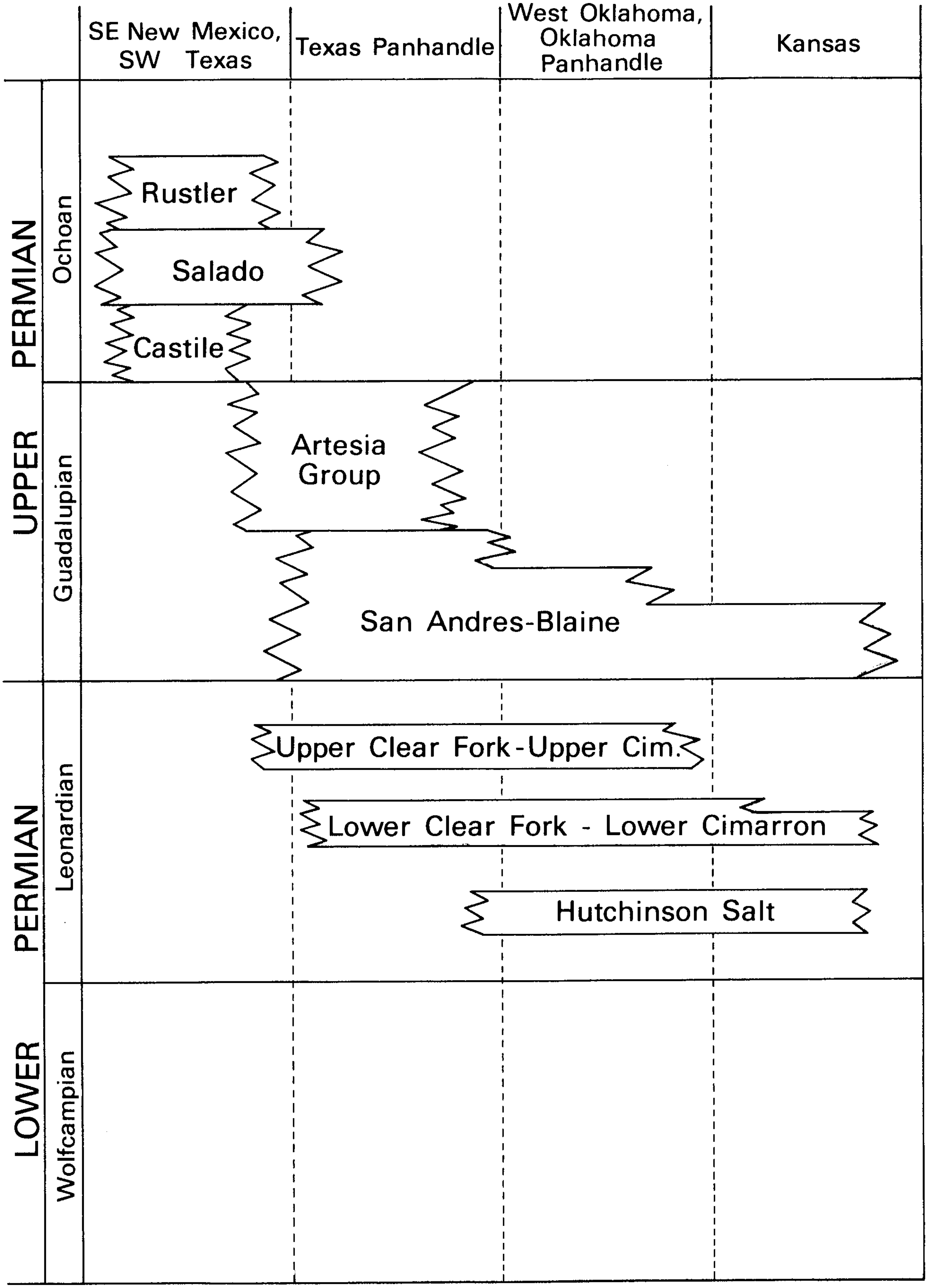


Figure 39. Diagram showing stratigraphic relationships of major salt-bearing units in Permian basin. Vertical dimensions are not related to thickness of salt units.

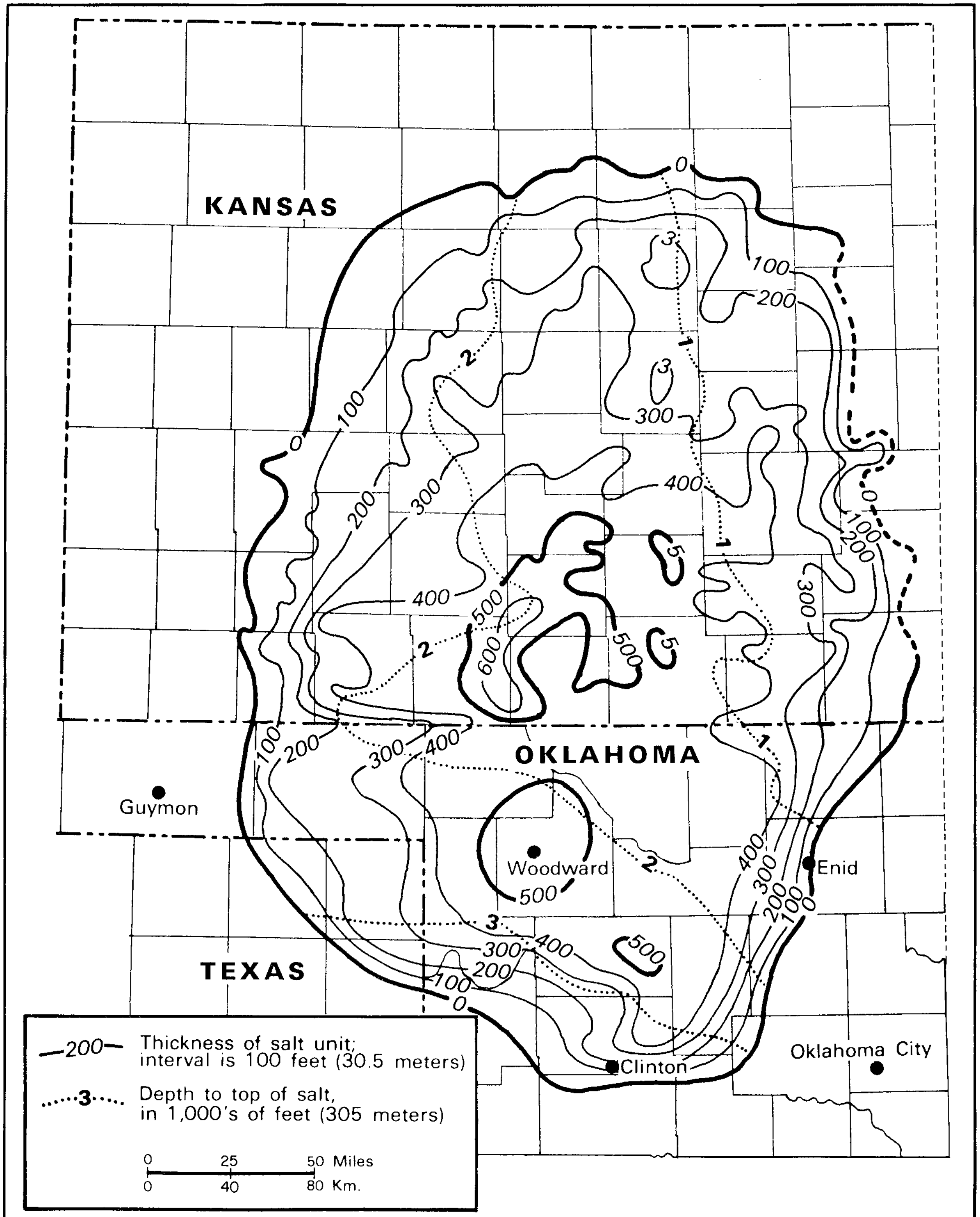


Figure 40. Map showing thickness in feet and depth to top of salt-bearing strata in Hutchinson salt member of Wellington Formation (from Schumaker, 1966; Bayne, 1972; Johnson, 1976).

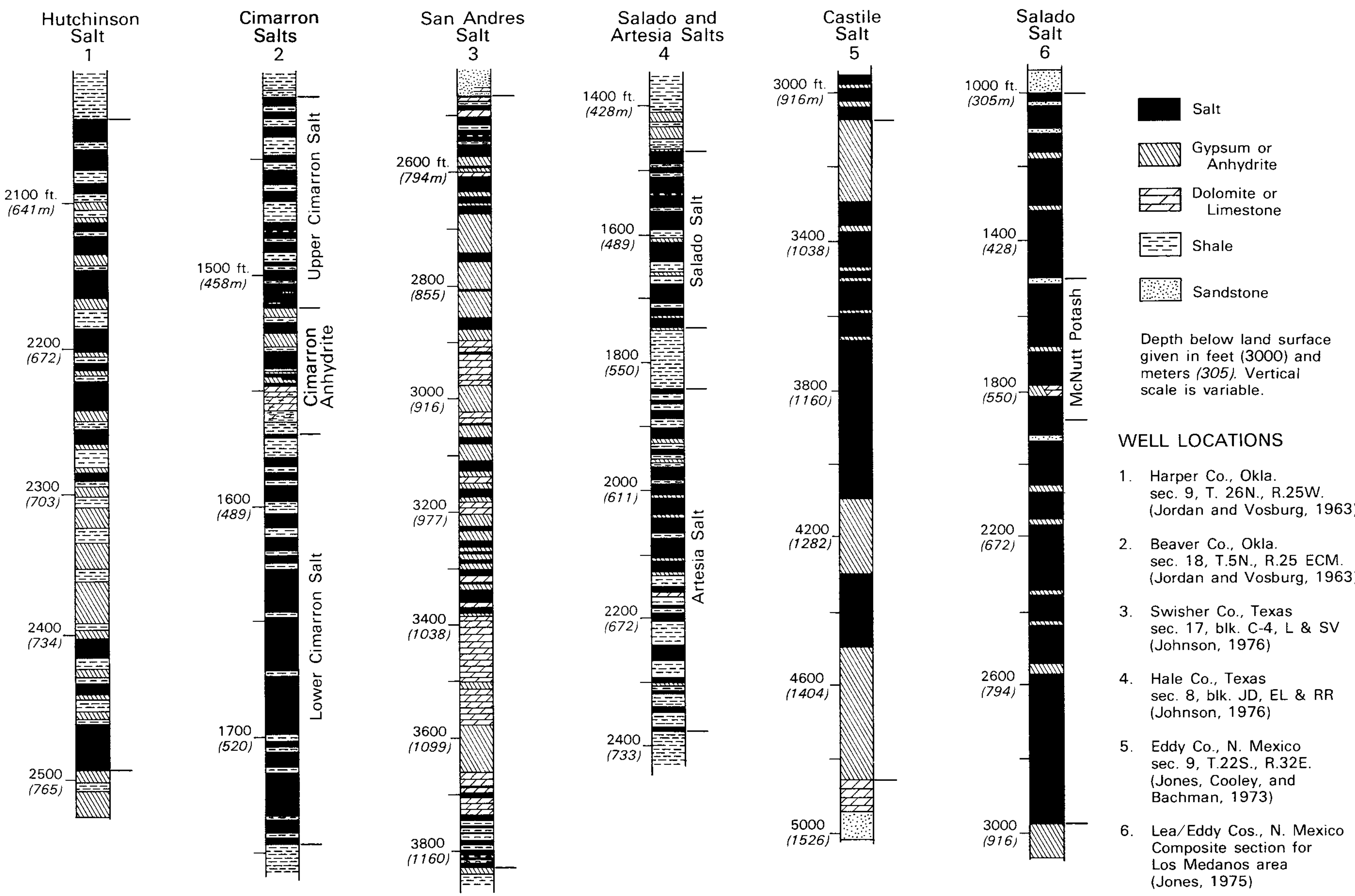


Figure 41. Representative well logs of major Permian salt units in Permian basin.

The Lower Clear Fork (Lower Cimarron) salt ranges in thickness from 60 to 150 m in most of the area extending from the western Palo Duro basin to the north flank of the Anadarko basin (fig. 42). Typical lithologies present are interbedded salt, shale, and anhydrite (fig. 41). Individual beds of rock salt are commonly 2 to 8 m thick and are interbedded with shale in the Anadarko basin and with anhydrite and shale in the Palo Duro basin. Shale and anhydrite beds are typically 0.5 to 5 or 6 m thick. Salt normally makes up 30 to 70 percent of the unit, but it makes up 78 percent of the unit in Beaver County, Oklahoma, where it is described from cores as halite with relatively few interbeds of reddish-brown or greenish-gray shale. Salt beds extend southward to within 30 to 60 km of the Midland and Delaware basins.

The top of the salt is about 100 to 1,800 m below the land surface in the area where it has been studied, with the depth generally increasing into the Anadarko and Palo Duro basins (fig. 42).

Upper Clear Fork (Upper Cimarron) Salt

The next youngest salt unit in the Permian basin lies directly above the Cimarron Anhydrite and is called the Upper Clear Fork salt in the Palo Duro and Dalhart basins and the Upper Cimarron salt in the Anadarko basin.

The Upper Clear Fork salt is commonly 30 to 180 m thick in the Permian basin (fig. 43). A thickness of more than 100 m is attained in most parts of the Palo Duro basin, with a maximum value of 180 to 200 m in Parmer County, Texas, and adjacent areas. In most parts of the Anadarko basin, only salty shale with some salt occupies the stratigraphic position of this principal salt unit. These salty strata are 15 to 180 m thick, but they do not contain enough salt to be considered a major salt unit. In a similar manner, 100 to 170 m of salty shale and some salt occupy this position in the Dalhart basin. The Upper Clear Fork salt extends southward to within 15 to 30 km of the Midland and Delaware basins.

Salt beds are typically 2 to 6 m thick and are interbedded with shale, anhydrite, and dolomite beds that also are 2 to 6 m thick. Layers of salt generally make up 30 to 50 percent of the entire unit in most parts of the region.

The top of the Upper Clear Fork salt is 300 to 1,500 m below land surface in most of the Palo Duro and Dalhart basins (fig. 43).

San Andres (Blaine) Formation Salt

Salt deposits associated with the San Andres Formation and the Blaine Formation are widely distributed in the northern part of the Permian basin. They are referred to as the San Andres Formation in the Palo Duro basin and farther southwest, but in the Anadarko, Dalhart, and eastern Palo Duro basins they are subdivided into the Flowerpot salt, the Blaine Formation, and the Yelton salt, in ascending order.

The San Andres salt and the salts associated with the Blaine Formation constitute one of the thickest salt-bearing units in the region. These evaporitic strata are 250 to 500 m thick in the central and western parts of the Palo Duro basin and 120 to 200 m thick along the axis of the Anadarko basin (fig. 44). Elsewhere, the salt-bearing unit is typically 60 to 120 m thick. Salt beds extend southward to an area about 30 km from the Midland basin.

Salt occurs in separate beds 2 to 6 m thick in some areas, and in other areas it occurs in massive units that are 15 to 60 m thick with only a few thin layers of shale (fig. 41).

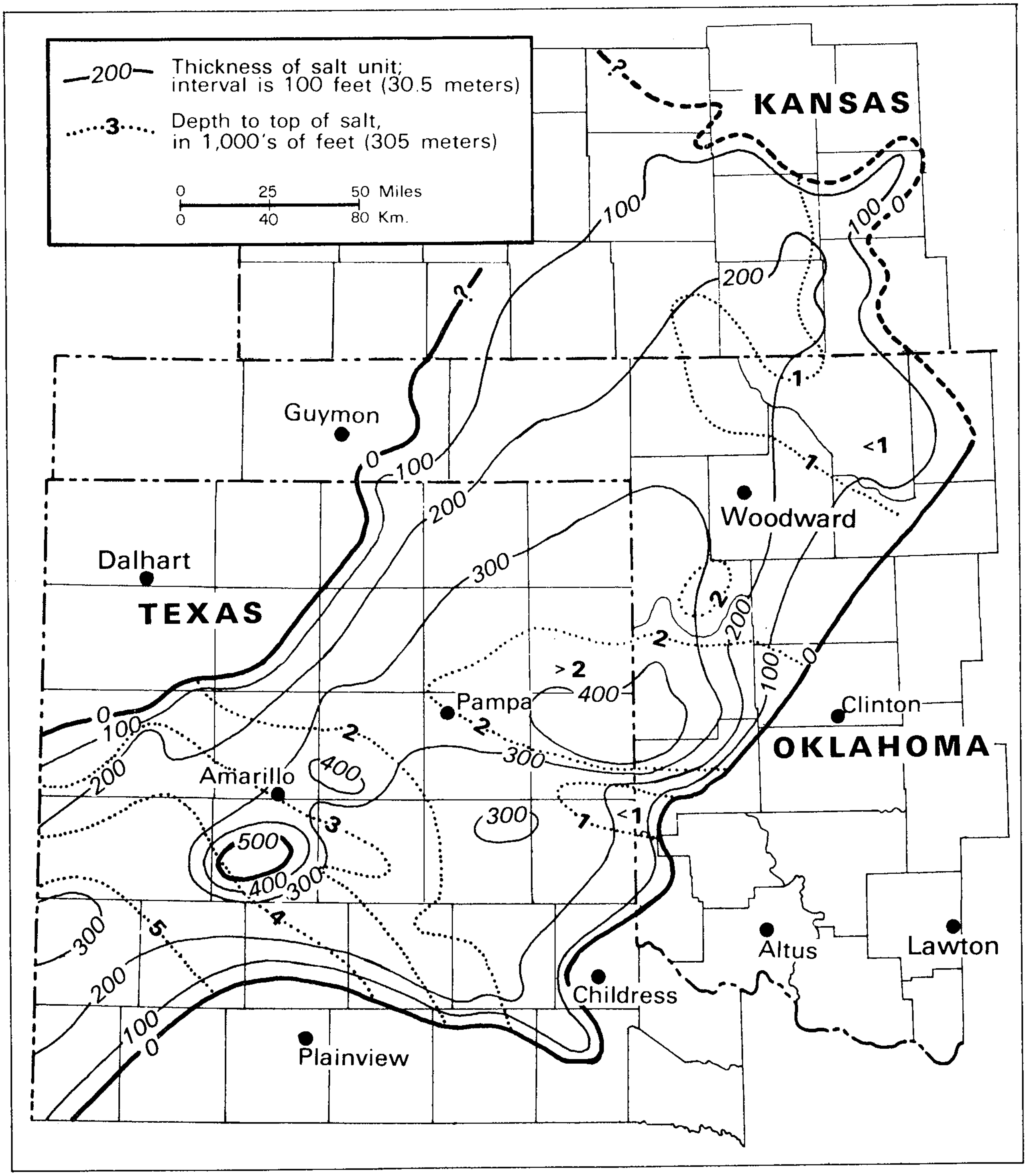


Figure 42. Map showing thickness in feet and depth to top of salt-bearing strata in Lower Clear Fork (Lower Cimarron) salt (from Schumaker, 1966; Bayne, 1972; Johnson, 1976).

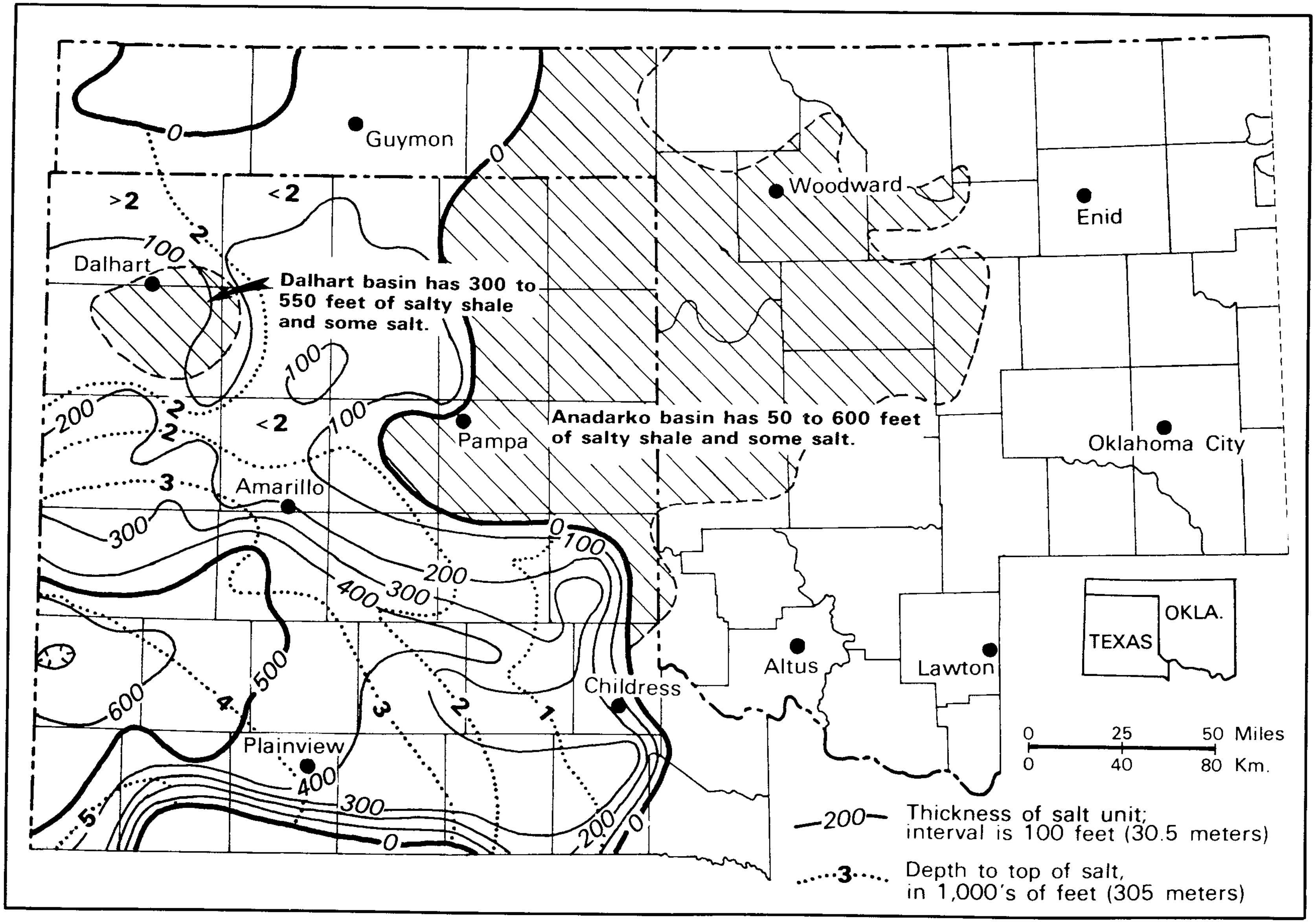


Figure 43. Map showing thickness in feet and depth to top of salt-bearing strata in Upper Clear Fork (Upper Cimarron) salt (from Johnson, 1976).

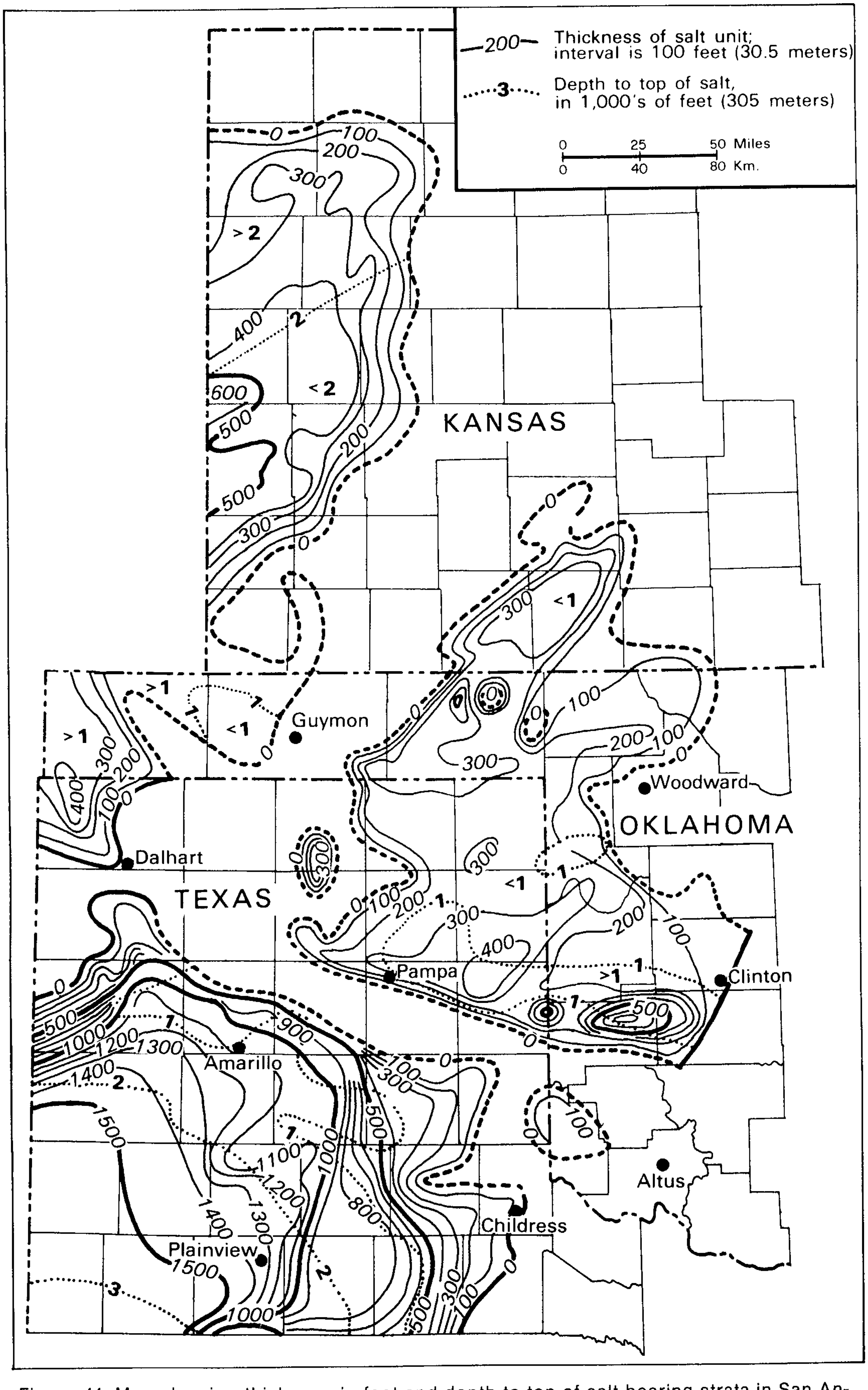


Figure 44. Map showing thickness in feet and depth to top of salt-bearing strata in San Andres Formation and equivalent strata (Flowerpot salt, Blaine Formation, and Yelton salt). From Schumaker (1966), Bayne (1972), and Johnson (1976).

Nonsalt strata consist of shale and some anhydrite in the north and anhydrite, dolomite, and shale in the south. The entire San Andres Formation is commonly 20 to 40 percent salt in much of the Palo Duro basin, whereas individual principal salt units are as much as 90 percent salt. The same general conditions exist farther west, as in the Clovis-Portales area of New Mexico (Jones, 1974). In the Anadarko and Dalhart basins, salt generally makes up 40 to 70 percent of the total mapped thickness, and constitutes 90 percent of some individual salt units.

Salt is currently limited to the deeper basin areas and has been dissolved from areas where it once was present over the Wichita-Amarillo and Cimarron uplifts. This unit has also been (and locally is being) dissolved in parts of Kansas (Bayne, 1972), northwestern Oklahoma (Johnson, 1976), and eastern New Mexico (Jones, 1974).

The depth to the top of the salt is less than 300 m in most parts of the Anadarko and Dalhart basins, but it reaches 430 m along the axis of the Anadarko basin and about 800 m in western Kansas (fig. 44). The top of the salt is 300 to 900 m below the surface is most parts of the Palo Duro basin.

Artesia Group Salt

The Artesia Group overlies the San Andres Formation and contains salt in the southern half of the region. As defined by Tait and others (1962), it consists of five formations, which are (ascending order) the Grayburg, Queen, Seven Rivers, Yates, and Tansill Formations. The major salt deposits of the Artesia Group occur within the Seven Rivers Formation.

The salt-bearing unit in the Artesia ranges from 30 to 180 m thick in the Palo Duro basin (fig. 45) but increases southward to 300 to 600 m in parts of the Midland basin (Adams, 1963). Individual salt beds in the unit are typically 2 to 20 m thick north of the Midland basin and are interbedded with shale and some anhydrite and sandstone (fig. 41). Salt makes up about 50 percent of the unit. In the Midland basin, the salts are interbedded with dolomites and sands. Salt has been dissolved locally from the Artesia Group on the eastern side of the Palo Duro basin and from the Clovis-Portales area of New Mexico.

The depth to the top of the salt is 300 to 600 m in almost all parts of the Palo Duro basin and appears to be 600 to 1,200 m in most parts of the Midland basin.

Castile Formation Salt

The Castile Formation, containing the oldest of the Ochoan salts, is restricted to the Delaware basin area of west Texas and southeastern New Mexico (fig. 46). This unit is differentiated from the salts of the overlying Salado because of an abundance of anhydrite in the Castile.

In general, the formation consists of 300 to 500 m of anhydrite and rock salt, but it is separated in the Los Medanos area of southeastern New Mexico into a lower and an upper anhydrite member separated by a middle member composed chiefly of salt (fig. 47) (Jones and others, 1973; Jones, 1975). Near the margins of the Delaware basin the three members merge into a single wedge-like mass of anhydrite. The middle salt member ranges in thickness from 170 to as much as 350 m in the Los Medanos area, where it is thickened locally by deformation, but it is generally 60 to 150 m thick in most parts of the Delaware basin. A medial anhydrite 30 m thick divides the salt member into a lower salt bed, which is free of interlaminated anhydrite-limestone layers, and an upper salt bed, which contains several of these layers up to 2 m thick.

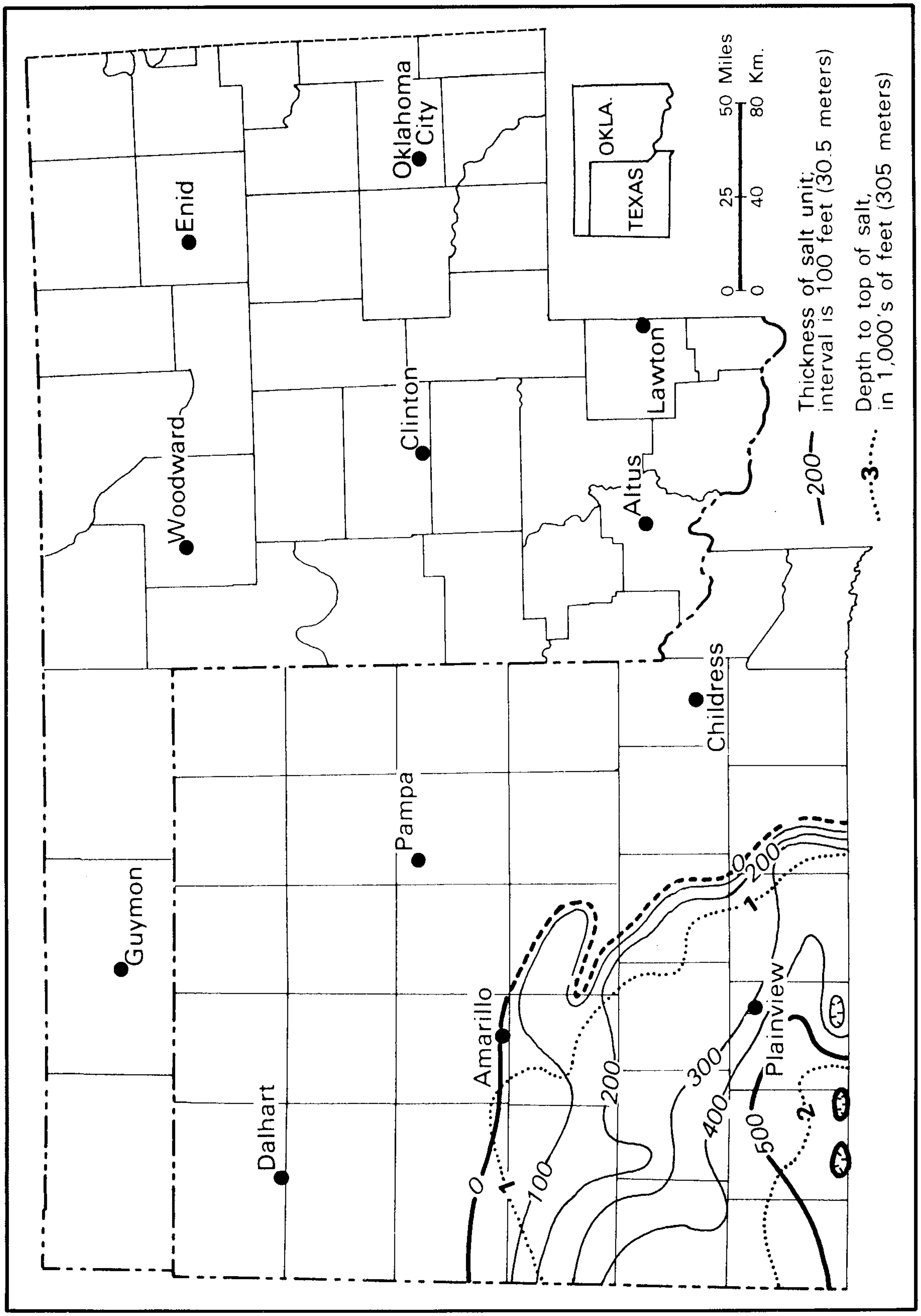


Figure 45. Map showing thickness in feet and depth to top of salt-bearing strata in Artesia Group (from Johnson, 1976).

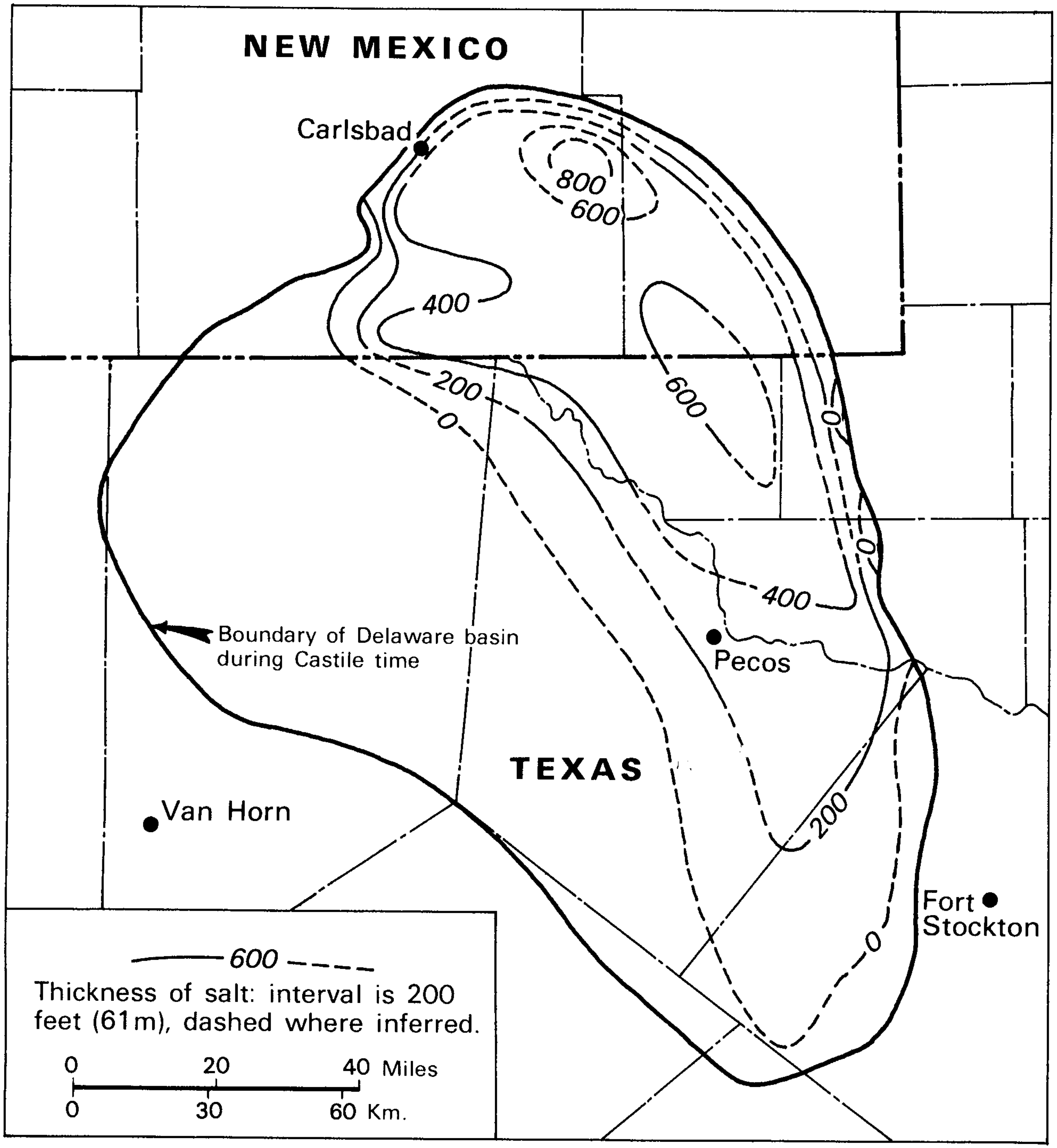


Figure 46. Map showing thickness in feet of salt in Castile Formation in Texas and New Mexico (from map by P. T. Hayes, presented in Pierce and Rich, 1962).

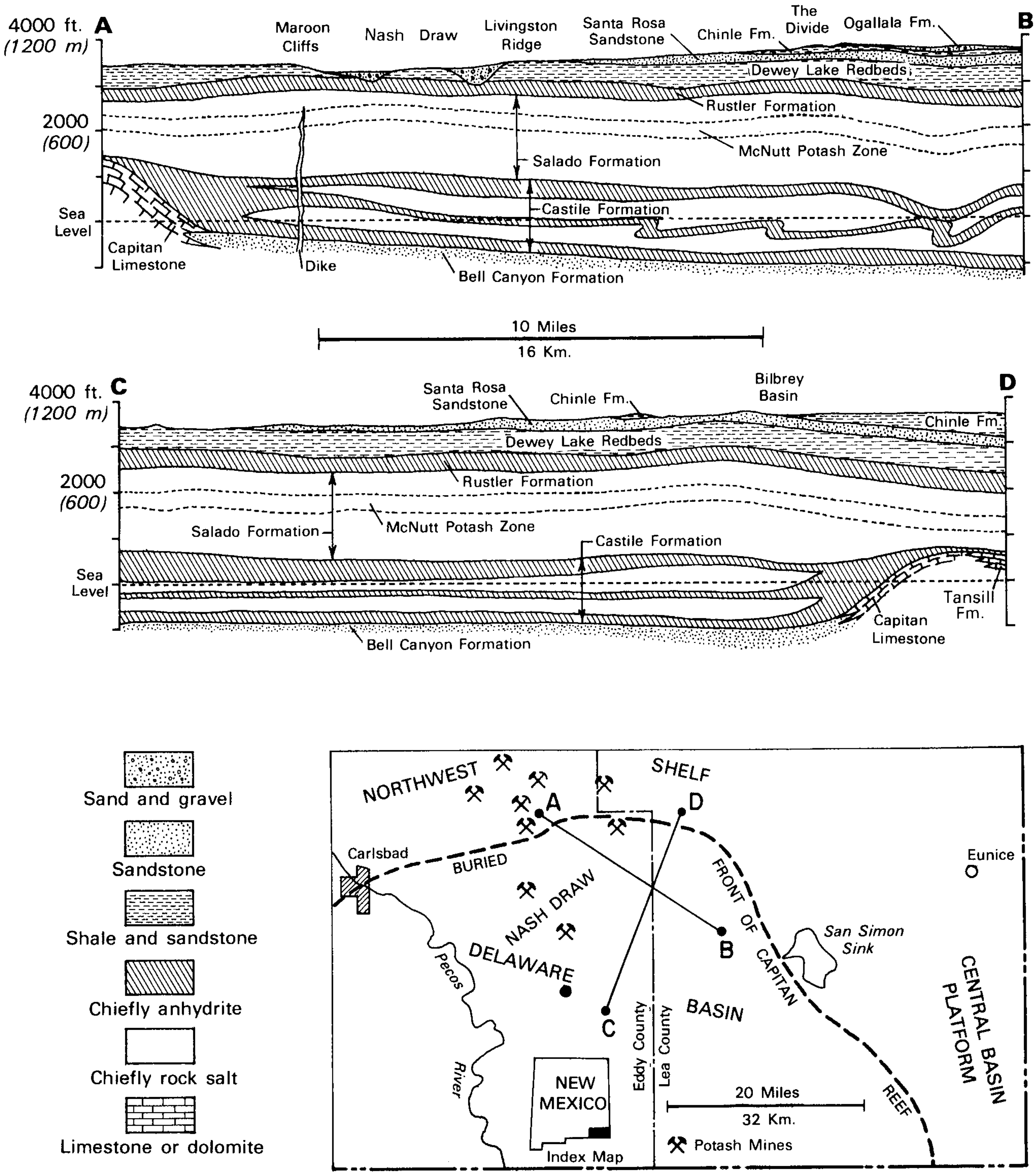


Figure 47. Geologic cross sections showing Permian salts in Carlsbad area of southeast New Mexico (modified from Jones and others, 1973).

The Castile Formation underlies the Los Medanos area at depths ranging from 500 m near the northwest corner of the area to 1,100 m near the southeast corner (Jones and others, 1973). This unit occurs generally at even greater depths farther to the south and southeast.

Salado Formation Salt

The Salado Formation is the principal salt-bearing formation of the Delaware-Midland basin area. This unit also contains the important potassium salts that are being mined in the Carlsbad area of southeastern New Mexico (Brokaw and others, 1972; Jones, 1975).

The Salado Formation is more than 600 m thick in the Delaware basin, where it reaches its maximum thickness, and consists mainly of salt (fig. 41) with some interbedded anhydrite and lesser amounts of shale, sandstone, and potash minerals. The salt alone is commonly 60 to 300 m thick and is locally more than 500 m thick (fig. 48). Rock salt makes up 80 to 90 percent of the unit in many areas. Abrupt thinning of the Salado salts on the east and west sides of the Delaware basin results largely from dissolution of the salt in the shallow subsurface.

In the Carlsbad area, the Salado is divided into unnamed lower and upper members, separated by a middle member known as the McNutt potash zone (fig. 47) (Brokaw and others, 1972; Jones, 1975). The three members are about equally rich in halite, anhydrite, polyhalite, and claystone, but only the McNutt member is rich in sylvite, carnallite, and other potassium- and magnesium-bearing minerals that make this the principal source of potash salts mined in the United States. In the Carlsbad area the lower member is about 300 m thick, the McNutt member about 100 m, and the upper member about 150 m.

To the north, in the Palo Duro basin, the Salado salts are grouped with some of the underlying salts from the Tansill Formation into a salt-bearing unit as thick as 100 m (fig. 49).

The depth to the top of the Salado salts is as shallow as 50 m to the west but is typically 300 to 750 m in most parts of the Delaware and Midland basin areas. Within the Palo Duro basin (fig. 49), the depth ranges from 300 to 600 m.

Rustler Formation Salt

The Rustler Formation is the youngest salt-bearing unit in the Permian basin and is limited to the Delaware and Midland basin areas. In the subsurface the formation is mostly anhydrite and salt, but it also contains interbeds of polyhalite, sandstone, and shale (Brokaw and others, 1972; Jones and others, 1973). Salt beds are 2 to 10 m thick and constitute about 40 percent of the unit where the salt has not been partly dissolved by meteoric water. The total thickness of the Rustler Formation is about 100 to 150 m in the Carlsbad area.

The depth to the top of salt beds in the Rustler Formation ranges from about 150 to 600 m in various parts of the Delaware and Midland basins.

Salt Dissolution

Dissolution of salt beds is now occurring at shallow depths, mainly in the eastern part of the Permian basin, or east of the High Plains. Saturated sodium chloride brines are

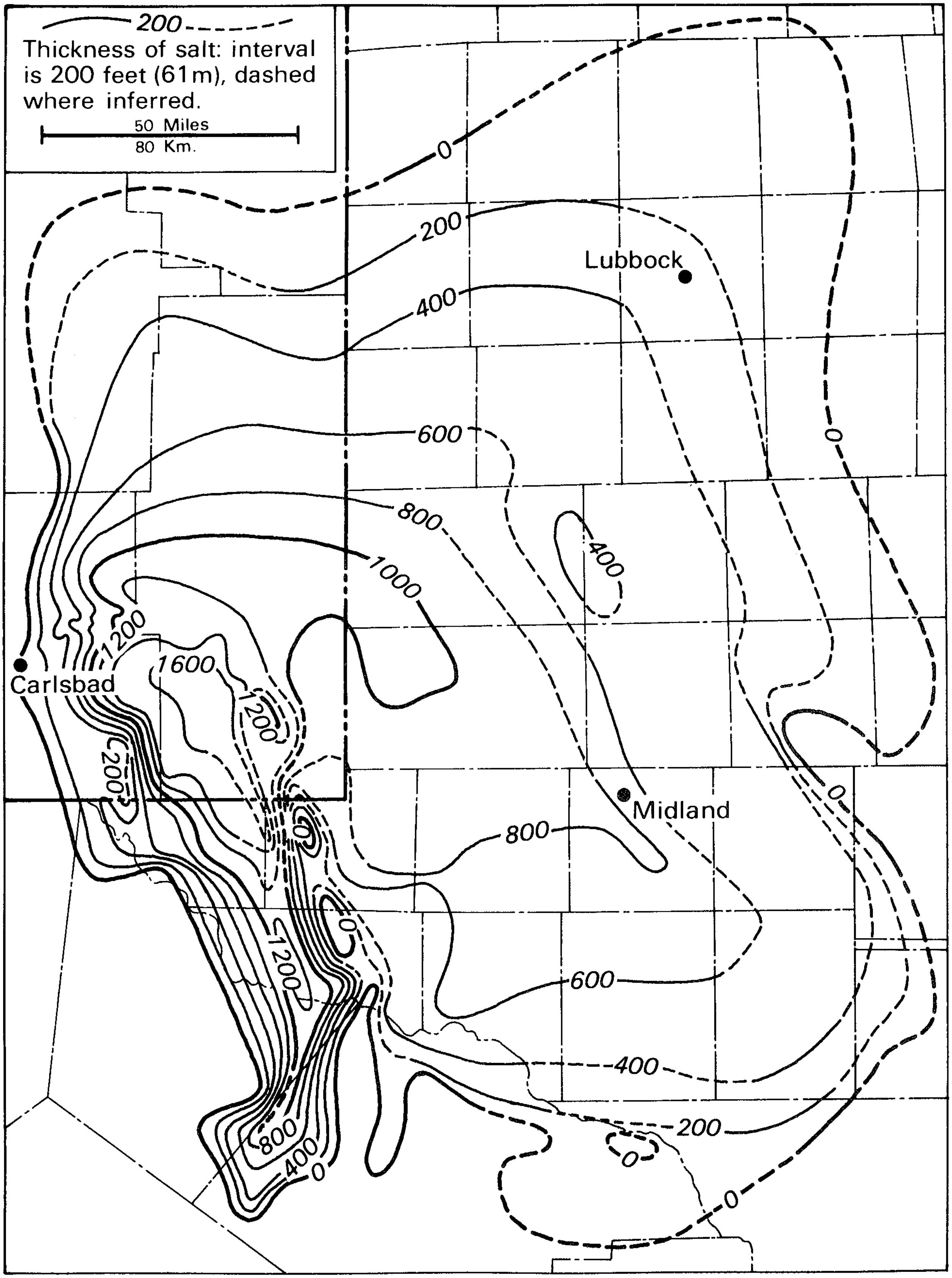


Figure 48. Map showing thickness in feet of salt in Salado Formation in Texas and New Mexico (from map by P. T. Hayes, presented in Pierce and Rich, 1962).

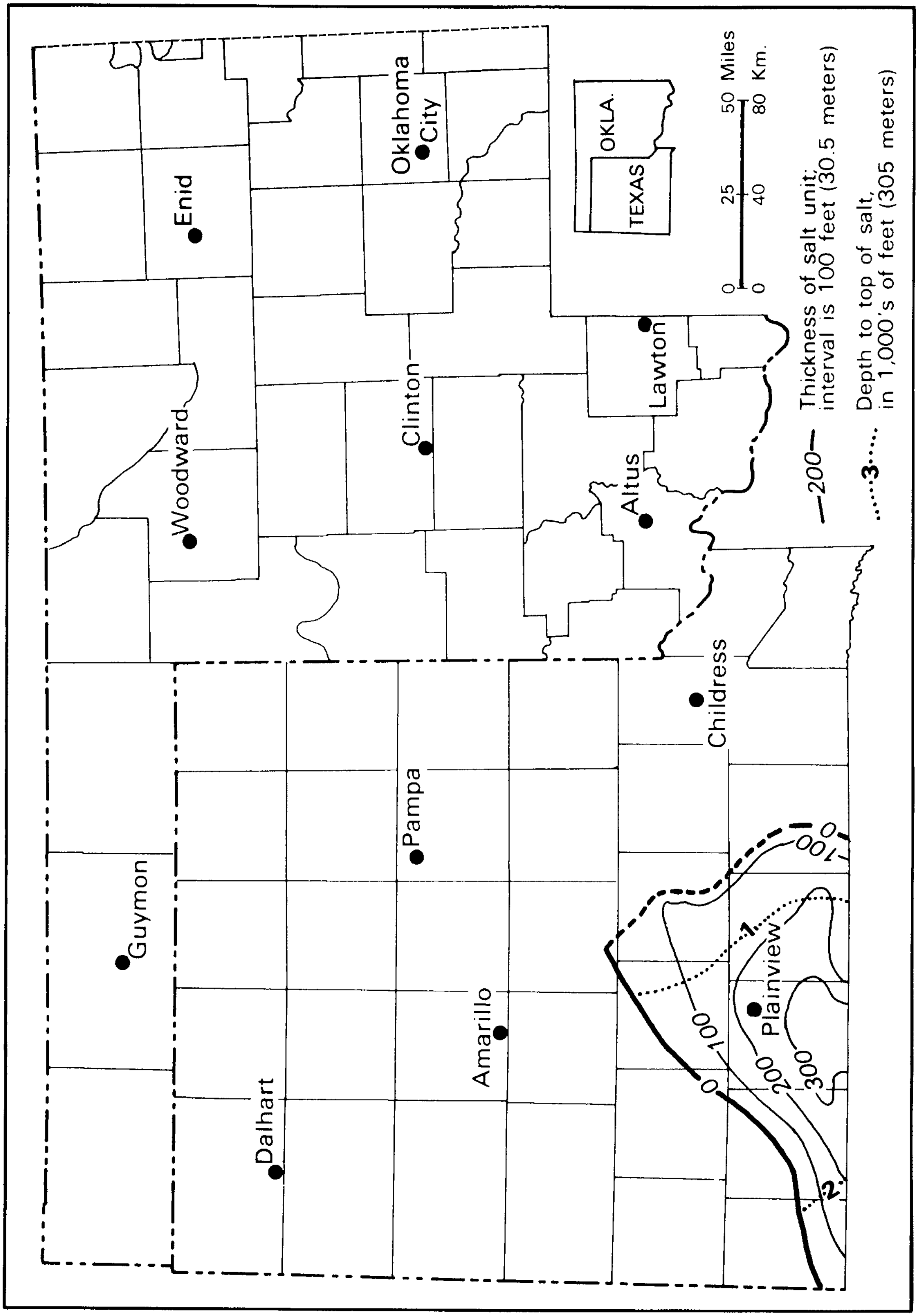


Figure 49. Map showing thickness in feet of salt-bearing strata in Salado-Tansill salt unit in Palo Duro basin area of Texas (from Johnson, 1976).

being emitted at the surface at many natural salt plains and salt springs in central Kansas, western Oklahoma, Texas, and southeastern New Mexico (Ward, 1963; Swenson, 1973, 1974; Johnson, 1976), and individual salt plains emit several hundred to as much as several thousand metric tons of salt daily. Most of the brine is produced from meteoric water that has percolated down to the shallow salt beds and has migrated only short distances to the discharge areas. Examples of man-induced salt dissolution (around brine wells and abandoned oil and gas boreholes) and land-subsidence problems in central Kansas are described by Walters (1976).

Many of the salt units are dissolved at various locations. The Hutchinson salt is undergoing dissolution locally along its eastern border in Kansas, and the Lower Cimarron salt is being dissolved along the Kansas-Oklahoma line. Salts associated with the Blaine Formation have been dissolved extensively in the past along the Amarillo uplift and northward to the Oklahoma Panhandle and western Kansas. Brine formed from these salts is currently being emitted in northwest and southwest Oklahoma and the eastern Palo Duro basin. Both the Artesia and Salado salts are locally being dissolved in the Palo Duro basin (Jones, 1974; Johnson, 1976), while the Castile, Salado, and Rustler salts all have been, or are being, dissolved in parts of the Delaware basin and nearby areas (Olive, 1957; Bachman and Johnson, 1973; Jones, 1973; Bachman, 1974; Hiss, 1976).

A tentative observation is that salt is being dissolved most commonly at depths of 150 to 250 m below the surface on the east side of the Permian basin, although at some places the dissolution occurs as deep as 300 m and at other places salt is still present as shallow as 10 m below the surface (Johnson, 1976). The areas where the salt beds are abruptly terminated by solution appear to coincide with the areas of brine emissions on the eastern side of the study region.

Dissolution of salt in the past has caused the leading edge of various salt units to recede downdip, back from the outcrop. Although these dissolution phenomena exist at shallow depths along the margins of the salt deposits, there are many large areas of the basin where salts at depths of 300 to 900 m are free of dissolution.

Hydrology

Surface Water

Surface drainage consists mainly of east-flowing streams and rivers whose headwaters are either in eastern New Mexico, in Colorado, or in the west Texas–Texas Panhandle area. Principal river systems crossing the area are, starting on the north: Kansas, Arkansas, Cimarron, North Canadian, Canadian, Red, Brazos, Colorado, and Pecos. These rivers are mostly supplied by precipitation and runoff, but some are locally recharged by springs emerging from the Ogallala and from Permian sandstone, gypsum, and dolomite aquifers. Average annual precipitation ranges from about 40 to 60 cm in the west to about 60 to 75 cm in the east part of the basin.

Streams and rivers crossing the region contain fresh water in the High Plains and in much of the area where they flow on Permian bedrock. Such surface waters are, however, degraded by natural sodium chloride brines emitted at many salt plains and salt springs in Kansas, western Oklahoma, in the southeastern Texas Panhandle, and in southeastern New Mexico where the rivers cross the shallow deposits of several salt units (Ward, 1963; Swenson, 1973, 1974; Johnson, 1976). In all cases, local meteoric water appears to have migrated down to the salt beds, from which it returns to the surface as saturated brine. The U.S. Army Corps of Engineers is currently studying salt springs and salt plains on the east side of the Permian basin in order to control the chloride emissions and improve water quality in the streams and rivers.

Ground Water

All bedrock formations in the region contain strongly saline water, except locally at and near the outcrop where they may be flushed by meteoric recharge (Swenson, 1974). Some excellent fresh-water aquifers are, however, present in the region. The Ogallala Formation of Tertiary age is the major source of ground water throughout the High Plains region and is widely used for municipal and irrigation water (Irwin and Morton, 1969). Large yields of fresh water are also obtained from the Dakota Sandstone in parts of Kansas and from the Rush Springs and Elk City Sandstones in western Oklahoma. In parts of Texas and New Mexico, principal fresh-water aquifers include the Santa Rosa Sandstone of the Triassic Dockum Group, the Edwards-Trinity aquifer of Cretaceous age, and the Capitan Limestone and Rustler Formation of Permian age. Throughout the region, thick deposits of Quaternary terrace and alluvial material also yield large supplies of fresh water along present-day and ancient courses of the major rivers.

Several sands and other rock units associated with salt beds contain saline waters in the subsurface. The Tubb sand is present between the Lower and Upper Clear Fork salts in much of the Texas Panhandle and surrounding area, and the Glorieta sand underlies the San Andres and Blaine Formation salts in New Mexico and the Texas and Oklahoma Panhandles. Gypsum and dolomite beds of the Blaine Formation are locally porous and contain salt-water brines along the east side of the Permian basin.

In almost all cases, the fresh-water aquifers of the basin are at fairly shallow depth; they are stratigraphically above and separated from the Permian salt deposits that might be used for waste storage. Additional studies are needed to better understand the relationships of the salt deposits to these aquifers and to the brine-filled sands and other rock units that are associated with the salts.

Seismic Activity

Recorded seismic activity in the Permian basin area is low, compared to most other parts of the United States. Earthquakes of Modified Mercalli Intensity V (MM V) or greater are sparse in the region (fig. 15). The only part of the salt basin that has undergone significant activity is near the Amarillo uplift and along the latter's west-northwesterly continuation across the Bravo dome and the Dalhart basin.

The entire region of investigation is within zone 1 on the seismic-risk map prepared by S. T. Algermissen (ESSA/Coast and Geodetic Survey, 1969) (fig. 16). Only 10 earthquakes of MM V or greater are known within the salt-study region (Coffman and von Hake, 1973). Two of the earthquakes occurred near the town of Panhandle, in Carson County, Texas, one in 1917 (MM VI) and the other in 1925 (MM V). Two earthquakes also occurred near Borger, in Hutchinson County, Texas, one in 1936 (MM V) and the other in 1966 (MM V). Other Texas earthquakes were recorded near Dalhart in Hartley County in 1948 (MM VI); in western Oldham County, just east of Nara Visa, New Mexico, in 1951 (MM VI); and in west Texas in 1966 (MM VI). A quake occurred near Amistad, New

Mexico, in 1970 (MM VI), and two events occurred in southwestern Kansas in 1904 (MM V) and in 1956 (MM VI).

Several earthquakes greater than MM VI have occurred outside the salt-study area in surrounding states. Oklahoma earthquakes include the El Reno event in 1952 (MM VII) and the Catoosa event in 1956 (MM VII). Earthquakes in Kansas were reported at Lawrence in 1867 (MM VII) and at Manhattan in 1906 (MM VII). One of the largest earthquakes was the one at Valentine, in west Texas, during 1931 (MM VIII). A total of four earthquakes of MM VII, VII-VIII, and VIII have been reported from Socorro, New Mexico, with one event in 1869 and the other three events in 1906. Two other earthquakes in New Mexico include an event near Valencia in 1893 (MM VII) and an event in Santa Fe County during 1918 (MM VII-VIII). One earthquake occurred along the New Mexico-Colorado border in 1966 (MM VII). An earthquake near Denver, Colorado, in 1967 (MM VII) was one of a series of events induced by the subsurface injection of waste materials.

Data used in compiling this section were taken mainly from Coffman and von Hake (1973), but additional information is contained in reports by Docekal (1970) and Northrop and Sandford (1972).

The low seismicity and low seismic risk of the area underlain by salt indicate that earthquakes should not represent a significant problem for waste storage in the Permian basin.

Mineral Resources

Oil and Gas

Major oil and gas fields are present within the Permian basin (fig. 50). Oil production comes mainly from the Delaware and Midland basins and nearby shelf and platform areas, whereas natural gas is produced mainly in the Panhandle and Hugoton fields that overlie the Amarillo uplift, Cimarron arch, and western Anadarko basin areas. Production is mainly from Permian and Pennsylvanian strata, with producing zones being below the lowest salt layers in almost all areas.

Current activity centers on the Anadarko basin and the Delaware and Midland basin areas. These areas will continue to attract exploration interest in years to come and will remain significant petroleum provinces within the continental United States.

Oil and gas are absent, or occur only in small fields, in and near the Palo Duro and Dalhart basins and in parts of western Kansas and eastern Colorado. The low ratio of successful wells drilled in these areas has inhibited exploration for petroleum, and thus waste storage in these basins probably would cause a minimum of interference with future oil and gas development.

Other gaseous minerals associated with oil and natural gas are also being produced in the Permian basin. Helium is produced in Cimarron County, Oklahoma, in Hansford and Moore Counties, Texas, and in several counties of southwestern Kansas. Carbon dioxide is produced from Permian rocks in Harding County, New Mexico.

It is clear, therefore, that the Permian basin contains large areas with abundant oil and gas production, but there are other substantial areas underlain by thick salts in the basin that are fairly free of boreholes with little potential for future petroleum production.

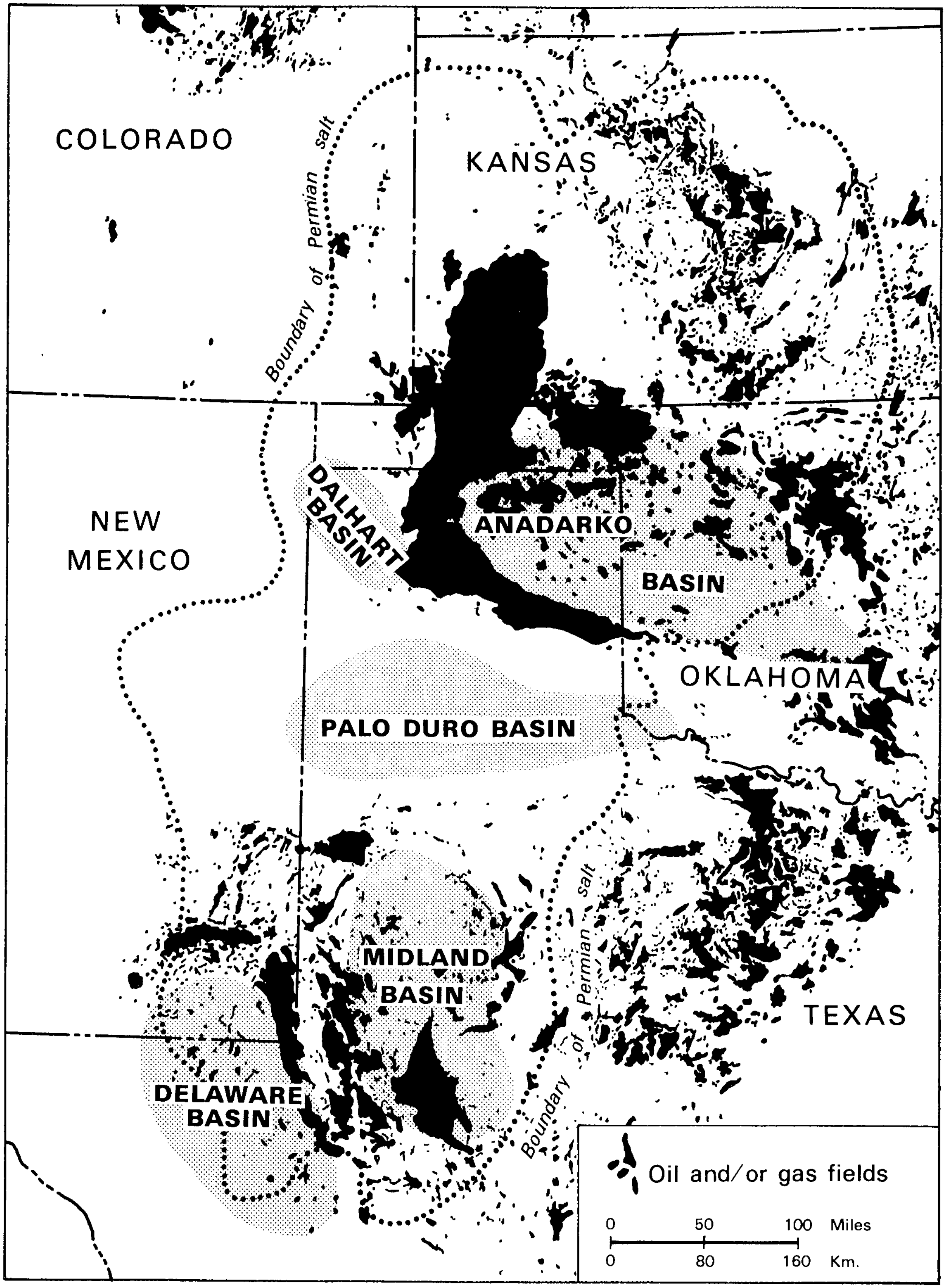


Figure 50. Map showing oil and gas fields in Permian basin and surrounding areas (modified from Petromotion, 1973).

Salt

Salt resources of the Permian basin are vast. Jordan and Vosburg (1963) estimated that nearly 20 trillion metric tons of salt is present in the Anadarko basin of Oklahoma and Texas alone. Salt is being recovered by mechanical- or solution-mining techniques at eight localities in central Kansas, including the mines at Hutchinson and Lyons (fig. 37). All eight operations are utilizing the Hutchinson salt, which in this area is 60 to 100 m thick and at a depth range of about 150 to 300 m. Salt is also produced by solution mining at three localities in Texas, and a small tonnage is produced by solar evaporation of brine-spring water at two salt plains in northwestern and southwestern Oklahoma (fig. 37).

Another use of the salt is underground storage of liquefied petroleum gas (LPG) in man-made cavities. Johnson (1976) reported 17 LPG-storage facilities in salts of western Oklahoma and the Texas Panhandle, and Walters (1976) reported 16 in salts of central Kansas.

Thick salt deposits are so widespread in the Permian basin that many areas can be found where past mining activity would not interfere with development of a waste repository.

Potash

Deposits of potash minerals are known only in the southern part of the Permian basin, namely in southeastern New Mexico and nearby parts of west Texas. Major minable resources appear to be restricted to the McNutt potash zone of the Salado Formation in the Carlsbad district, which covers the northern part of the Delaware basin and a part of the northwest shelf (Brokaw and others, 1972; Jones, 1975).

The Carlsbad district has been the major source of United States potash for many years. Potash minerals, chiefly sylvite and langbeinite, are mined underground by 7 companies, with 6 mines in Eddy County and 1 in Lea County. Polyhalite, a potash mineral of little or no current economic importance, is more widely distributed in west Texas within beds of anhydrite in the Salado Formation.

The Carlsbad district contains 86 percent of the United States production capacity and 65 percent of the nation's potash reserves exploitable by current methods (Jones, 1975). Therefore, any selection of a waste-storage site in the Carlsbad district must be done so as not to conflict with present or future development of these important potash resources.

Other Minerals

Gypsum and anhydrite resources of the region are also great. They occur in rocks of Permian age, and several open pits are operated in areas underlain by salt in Barber County, Kansas, and Blaine County, Oklahoma. Other gypsum mines in these two states and Texas lie outside the salt area.

Other minerals now produced in salt areas of all states include sand and gravel, clays, and stone. In addition, volcanic ash is produced in Kansas and Oklahoma, and cement, sodium sulfate, and magnesium chloride are produced in Texas (U.S. Bureau of Mines, 1972).

All of these operations are relatively small surface mines or plants, and there should be no conflict between the continued use of surface minerals and the use of underground salt beds for radioactive-waste storage (except in the immediate vicinity of a storage site).

Regional Evaluation for Storage of Radioactive Waste

Based upon the review of available geologic data, some of the salt deposits in the Permian basin may prove to be suitable for underground storage of radioactive waste. Some deposits have thick, massive beds of rock salt (halite) at moderate depth. They are not structurally deformed or fractured, and there are large areas where the salt has not been dissolved. Almost the entire region has been tectonically stable since deposition of the salt beds, and the few recorded earthquakes in the salt region seem to be related primarily to one tectonic province, the Amarillo uplift. Almost all lands are rural, sparsely populated, and used for agriculture or ranching; the climate is semiarid, with average annual precipitation ranging from 40 cm in the far west to 75 cm in the east.

Petroleum exploration and production have been extensive in parts of the Anadarko, Delaware, and Midland basins and on the adjacent platforms and uplifts. Many boreholes have been drilled through the salt deposits in these areas, which constitute some of the major oil and gas provinces of the United States. The areas in and around the Palo Duro and Dalhart basins, on the other hand, have had few test holes drilled through the salts. Oil is not produced at all in the Palo Duro basin and is produced from only a few small fields in the Dalhart basin. Neither basin is currently regarded as a significant petroleum province. Boreholes and petroleum production are also sparse in large areas of western Kansas and eastern Colorado where thick salts are present at moderate depths.

There appear to be few areas in the region where storage of waste might conflict with the continued or future use of the nonpetroleum resources of the region. Potash minerals are intimately associated with the thick salts in and around the Carlsbad district of southeastern New Mexico, and present and future uses of this resource must be assessed. Salt is being solution mined at several sites and also is being used at a number of scattered localities for underground storage of LPG.

A total of eight principal salt units are present in various parts of the Permian basin. Thick salts are present at moderate depths in each of the five separate structural basins and locally on the adjacent uplifts. The Palo Duro basin is underlain by five salt-bearing units, including the Lower Clear Fork, Upper Clear Fork, San Andres, Artesia, and Salado salts (fig. 38). Four salt units, the Hutchinson, Lower Cimarron, Upper Cimarron, and Blaine Formation salts, are present in the Anadarko basin and parts of western Kansas. The Delaware basin contains the Castile, Salado, and Rustler salts, whereas the Midland basin has the Artesia Group, Salado, and Rustler salts. The Dalhart basin is underlain only by salts of the Blaine Formation.

Ground-water resources are important in most parts of the region, and the geohydrologic relationship of the several major fresh-water aquifers to salt-bearing strata needs further study. Special attention must also be paid to salt-dissolution features on both the east and west sides of the Permian basin.

In summary, it appears that many of the regional characteristics favorable for waste storage may be met in parts of the Palo Duro and Dalhart basins as well as in parts of northeastern New Mexico, southeastern Colorado, and western Kansas.

PARADOX BASIN

Structure and Geologic Framework

The Paradox basin comprises about 30,000 sq. km in southeastern Utah and southwestern Colorado that are underlain by thick salt deposits (fig. 51). The basin is in the northern part of the Colorado Plateau and is bounded by the Uncompahgre uplift on the northeast; by the San Rafael, Monument, and Defiance uplifts on the west and south; and by the San Miguel, San Juan, and La Plata Mountains on the east and southeast.

Salts in the Paradox basin occur in the Paradox Member of the Pennsylvanian Hermosa Formation. In much of the basin these salts lie at depths greater than 1,500 m, but in a series of long and narrow salt anticlines located on the northeast side of the basin the salts are at relatively shallow depths (Elston and Shoemaker, 1961; Hite and Lohman, 1973). The central or salt-bearing cores of the anticlines are about 700 to 4,000 m thick and consist of thick salt (halite) units interbedded with black shale, dolomite, anhydrite, and (locally) potash. Salt Valley anticline, on the north side of the basin, was recommended by Hite and Lohman (1973) as a salt anticline having good potential for radioactive-waste storage. Later work by Gard (1976) and Hite (1977) concentrated on this particular area.

The Paradox basin contains a wedge-shaped sequence of sedimentary rocks that overlies a basement complex of Precambrian crystalline rocks (fig. 52). About 500 to 1,000 m of pre-Paradox strata, mostly limestones and dolomites, was deposited in marine waters that covered the basin during most of Cambrian through Early Pennsylvanian time (Baars, 1966).

The basin subsided rapidly during Middle Pennsylvanian time, which brought on deposition of the thick series of evaporites in the Paradox Member of the Hermosa Formation. A total of 29 evaporite cycles were deposited in the basin during periods of transgression and regression.

Normally overlying the evaporites of the Paradox Member is an unnamed limestone that is the upper member of the Hermosa Formation (fig. 52). In many parts of the basin, however, this normal sequence has been modified by development of the salt anticlines, and the salt is overlain by a cap-rock material containing mixtures of anhydrite (gypsum at the outcrop), dolomite, and black shale.

The stratigraphic sequence and distribution of individual formations deposited after Pennsylvanian time vary considerably from one salt anticline to another, and most formations pinch out locally. This variation results from the fact that many of the salt cores in the anticlines were uplifted in a series of pulses, so that some formations either were not deposited upon the rising structures or were eroded shortly after deposition (Hite and Lohman, 1973).

Post-Pennsylvanian strata are represented by dominantly continental sandstones and shales, except for a sequence of about 1,000 m of gray marine shales of Late Cretaceous age (fig. 52). With withdrawal of the seas at the end of the Cretaceous, the area has remained above sea level and has been subjected to a long period of erosion. As a result, the total thickness of sedimentary rock remaining in the basin ranges from about 5,600 m along the northeast edge, near the Uncompahgre uplift, to about 2,000 m in the southwestern part of the basin.

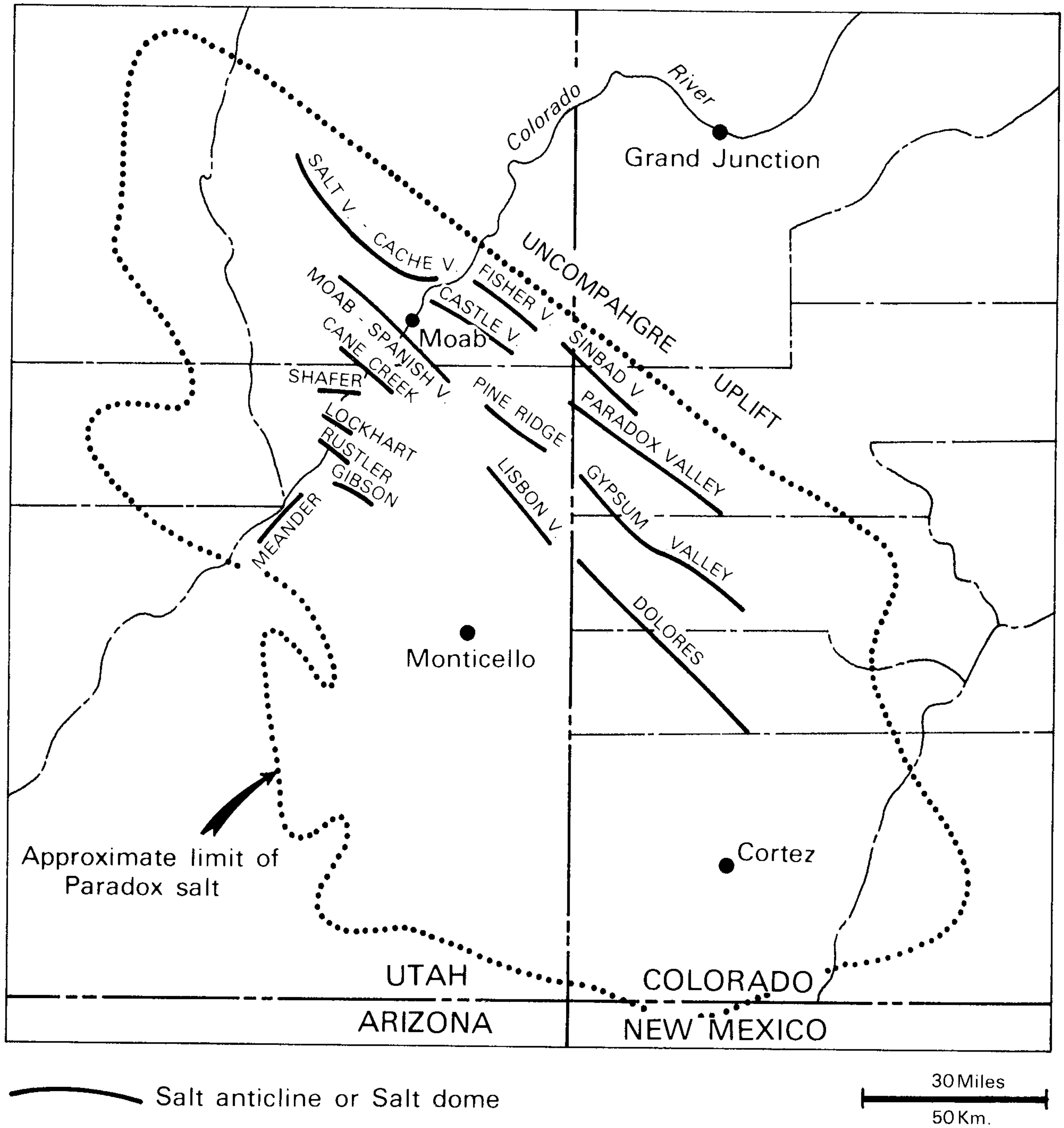


Figure 51. Index map of Paradox basin showing distribution of Paradox salts and location of salt anticlines in northeast part of basin (modified from Hite and Lohman, 1973).

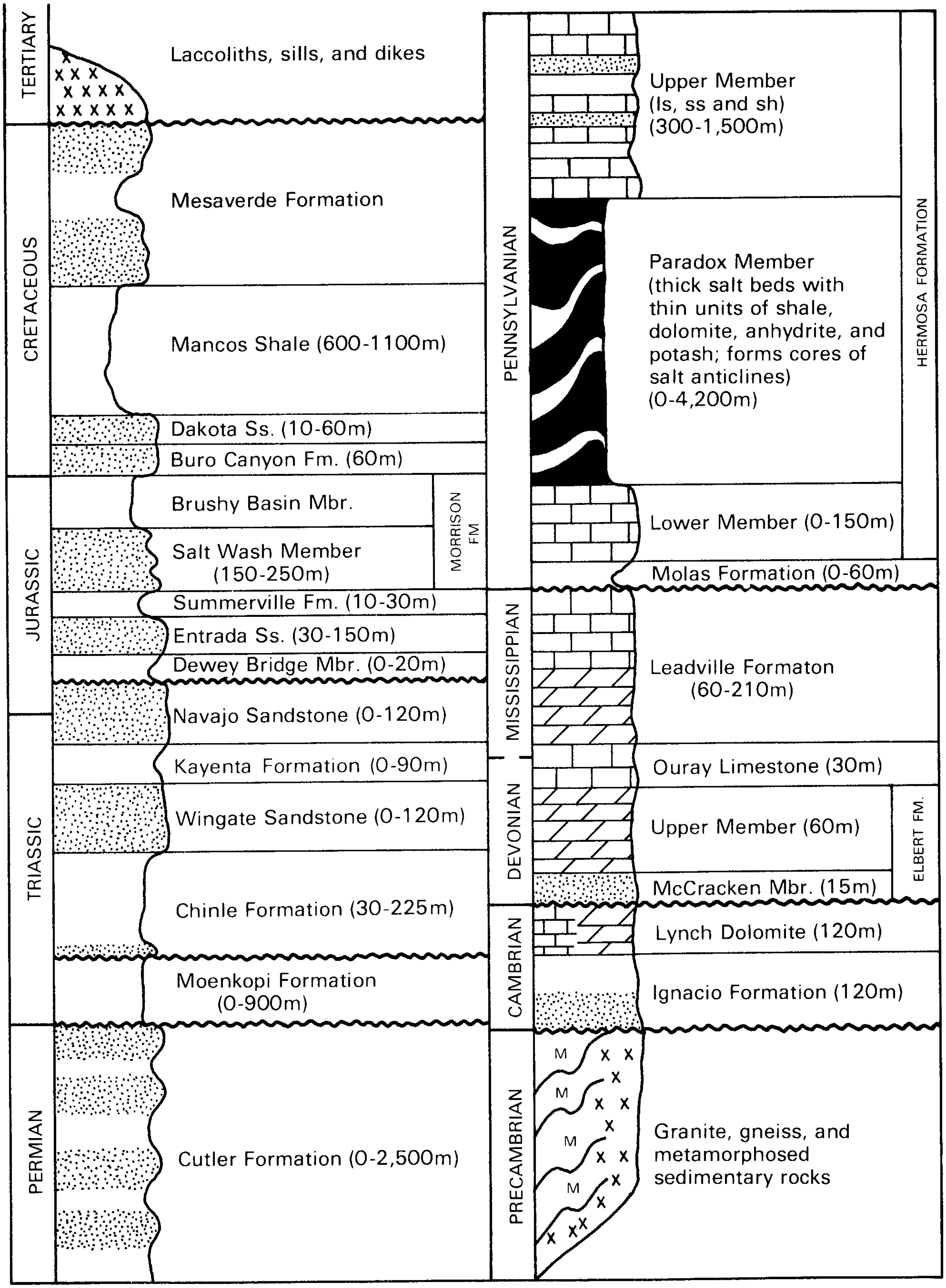


Figure 52. Generalized stratigraphic column for northeast part of Paradox basin (modified from Hite and Lohman, 1973).

Salt Deposits

Paradox Member of Hermosa Formation

The extensive evaporite deposits of the Paradox basin are of Middle Pennsylvanian age and occur in the Paradox Member of the Hermosa Formation. Bedded rock salt (halite) is the dominant lithology in the evaporite sequence. Directly above and below the Paradox Member are unnamed carbonate units that are considered to be upper and lower members of the Hermosa Formation (fig. 52).

Salt and other evaporites underlie an area of 30,000 sq. km in southeastern Utah and southwestern Colorado, but the greatest thickness of evaporites is in the trough-like depression adjacent to the Uncompahgre uplift on the north side of the basin. The original thickness of the evaporites in the trough area is estimated to have been between 1,500 and 1,800 m (Hite and Lohman, 1973). Flowage of salt in the numerous diapiric salt anticlines of the region has, however, caused the present thickness to vary from 0 to more than 3,000 m in a horizontal distance of 5 km or less. The maximum thickness of evaporites in the salt anticlines is nearly 4,200 m. In most areas the top of the salt is more than 1,500 m below the present land surface, except where it has flowed into the salt anticlines and is now at much shallower depths.

The Paradox Member evaporites consist of a sequence of cyclic sediments that include black shale, dolomite, anhydrite, halite, and (in some cycles) potash (fig. 53). A total of 29 evaporite cycles have been recognized in the deeper parts of the basin, and these have been numbered 1 through 29 in descending order (Hite, 1960; Hite and Liming, 1972; Hite and Lohman, 1973). Individual evaporite cycles are commonly 30 to 100 m thick. Each evaporite cycle can be correlated for considerable distances across the salt basin, although the correlation is difficult where beds have been folded, faulted, and deformed by flowage in the salt anticlines. More complete discussion of the evaporites and evaporite cycles is given in the reports by Herman and Sharps (1956), Herman and Barkell (1957), Hite (1968, 1970), Peterson and Hite (1969), and Hite and Lohman (1973).

Halite is the dominant rock in almost all areas, and massive beds of rock salt typically are 20 to 80 m thick (fig. 53). The rock salt, essentially the same as in other marine-evaporite deposits, consists of an intergrowth of halite crystals that range in size from 2 to 50 mm and average about 5 mm (Hite and Lohman, 1973). The salt is generally a smoky-gray color, except where small amounts of potash minerals with associated hematite impart a tan or red color.

Halite in the Paradox Member generally contains less than 2 or 3 percent of minerals insoluble in water (Hite and Lohman, 1973). Anhydrite is the principal insoluble mineral, although trace amounts of dolomite, clay, quartz, and talc may also be present. About one-third of the salt beds in the Paradox Member contain potash deposits (sylvite and carnallite) in some part of the basin.

Between each pair of halite units is a sequence of black shale, dolomite, and anhydrite, with an aggregate thickness that commonly is 10 to 20 m (fig. 53). Black shales, the dominant lithology among this group of rocks, contain clay minerals, quartz, and feldspars, and about 20 to 30 percent by weight is dolomite and calcite; organic matter is an important constituent and locally makes up as much as 15 percent of the rock. Layers of dolomite and anhydrite are dense and impermeable, except where fractured. Some flows of brine and/or oil and gas have been encountered locally in these rocks and in the shales where they have been intensely fractured.

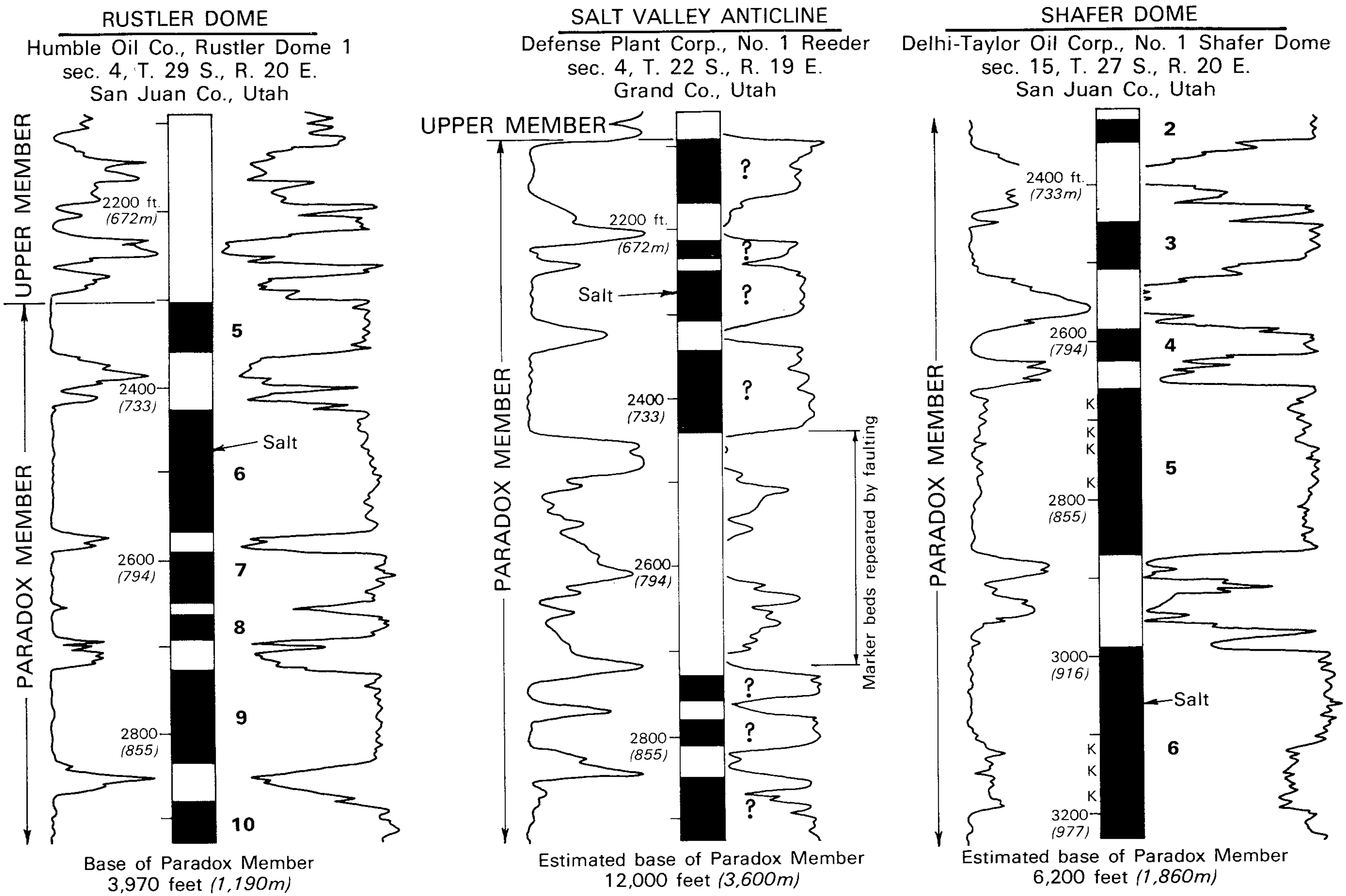


Figure 53. Gamma-ray/neutron logs and lithologic interpretation of Paradox Member of Hermosa Formation in three salt anticlines of Paradox basin. Dark units are salt (halite), shown with their numerical nomenclature, and light units are marker beds of black shale, dolomite, and anhydrite. Letter *K* indicates potash minerals. Modified from Hite and Lohman (1973).

Salt Anticlines

The major structural features of the Paradox basin are the salt-core anticlines in the trough-like depression on the northeast side of the basin (fig. 51). These anticlines, which occupy an area about 80 km wide and 200 km long, consist of long, undulating welts of thickened salt over which the younger rocks are arched in anticlinal form (Shoemaker and others, 1958; Cater, 1970; Hite and Lohman, 1973). There are five major anticlinal systems in the basin, and separate names have been given to the more pronounced segments of each system where the anticlines are breached and the surface expression is a prominent flat-floored valley. The major salt-anticline systems are (1) Lisbon Valley–Dolores Valley, (2) Moab Valley–Spanish Valley–Pine Ridge, (3) Gypsum Valley, (4) Castle Valley–Paradox Valley, and (5) Salt Valley-Cache Valley–Fisher Valley–Sinbad Valley (fig. 51). Several smaller anticlines or domes that lie just southwest of Moab along the Colorado River include Cane Creek anticline, Shafer dome, Lockhart anticline, Rustler dome, Gibson dome, and Meander anticline.

A typical anticline consists of three major components: floor, central core, and overlying or flanking strata (Hite and Lohman, 1973) (figs. 54, 55). The floor is made up of 450 to 750 m of nonevaporite sedimentary rocks that are older than the Paradox Member. These strata overlie a rigid basement complex and have been deformed primarily by block faulting and strike-slip faulting. The central core consists of halite and associated strata of the Paradox Member that were deformed plastically as they flowed into the anticline from adjacent areas. The overlying or flanking strata are a sequence of younger nonevaporite rocks that range in thickness from 1,500 to 4,500 m. The latter were gently arched during upward movement of the central core of evaporites and commonly are broken by high-angle normal faults where the underlying evaporites have been partly dissolved.

The central cores of the salt anticlines range in thickness from about 700 to 4,000 m (Hite and Lohman, 1973) and are made up of about 70 to 80 percent halite and associated potash minerals; the remainder consists of black shale, anhydrite, and dolomite marker beds. The structure of the central core has resulted from both regional compression and flowage of the evaporites, and it contrasts sharply with the structure of underlying and overlying nonevaporites (fig. 55).

Dissolution of halite at the upper surface of the central core has caused local development of a cap rock of insoluble material along the crest of the salt anticlines (Hite and Lohman, 1973). Cap rock in this area differs somewhat from that on Gulf Coast salt domes, inasmuch as the Gulf Coast variety was formed entirely from thin laminae and small crystals of anhydrite disseminated in the halite whereas the Paradox basin cap rock includes this type of material and even greater amounts of insoluble material from the marker beds. Anhydrite in the Paradox cap rock generally has been converted to gypsum. The amount of salt dissolved to produce cap rock in the various anticlines ranges from perhaps 100 to 1,000 m. The cap rock is generally porous, and in some anticlines it is saturated with brine.

Salt Dissolution

Past and/or present dissolution of salt in the Paradox basin is apparently limited to the western and southeastern edges of the salt basin and to the crestal areas of the salt anticlines (Hite and Lohman, 1973). Downdip dissolution of the salt along the margins of the basin has probably advanced no more than 3 to 5 km since the end of Pennsylvanian time

(280 million years ago), and thus basin-edge salt dissolution should not affect storage of radioactive waste well inside the basin margins.

Salt is now being dissolved locally along the upper surface of the evaporite sequence in some of the anticlines. Rivers draining the Paradox basin apparently are increasing their dissolved load of sodium chloride by about 610 metric tons per day (Hite and Lohman, 1973). Not known at this time, however, is how much of this is coming from the Paradox Member in salt anticlines and how much is being derived from younger rocks and other sources. The current rate of salt dissolution is thus unknown.

The distribution of cap rock in the central part of salt anticlines also shows those areas where salt dissolution has occurred in the past, and the thickness of the cap rock is a good indication of the amount of salt that has been removed. The average thickness of cap rock over the anticlines is about 300 m, and Hite and Lohman (1973) estimated that this represents the residue after dissolution of salt from about 900 m of halite-bearing rock in the central core. Because the dissolution occurred intermittently over a very long period of geologic time, this relatively slow process should not affect the isolation of radioactive waste stored at moderate depths below the cap rock.

Salt Valley Anticline

One of the structures that appears to have potential for radioactive-waste storage (based on present knowledge) is the northwest end of Salt Valley anticline, between Arches National Monument and the small village of Crescent Junction (fig. 54). This area was first studied geologically in detail by Dane (1935) and later was recommended by Hite and Lohman (1973) as one of the areas having high potential in the region for waste storage. Further study by the U.S. Geological Survey centered on an evaluation of the geology, hydrology, mineral resources, and geothermal gradient of the north end of the structure (Gard, 1976; Hite, 1977).

The top of the salt body is as shallow as about 250 m below the surface at places along the crest of Salt Valley anticline (fig. 55). Cap rock is exposed in the floor of the valley, and the underlying salt core is more than 3,000 m thick. Although there is uncertainty now about stratigraphic correlation of individual rock units locally in this area, borehole data show that individual salt units at least 15 to 30 m thick are present at minable depths (fig. 53). The area also is accessible by highway and railroad, is remote from human activity, and is on State and Federal lands.

Hydrology

Surface Water

The Colorado River and its principal tributaries dominate the drainage system of the Paradox basin. Principal tributaries are the Green, San Juan, and Dolores Rivers; the latter stream drains most of the salt-anticline area. These rivers are supplied mainly by precipitation and runoff, although a few springs are present. Most of the smaller tributaries are ephemeral. Average annual precipitation ranges from about 20 to 40 cm in the low desert areas that make up most of the Paradox basin to more than 75 cm in the adjoining high mountain areas.

Springs occur mainly in the high mountain areas or in the Uncompahgre Plateau. The few springs present in the lower salt-anticline region are small and typically in the

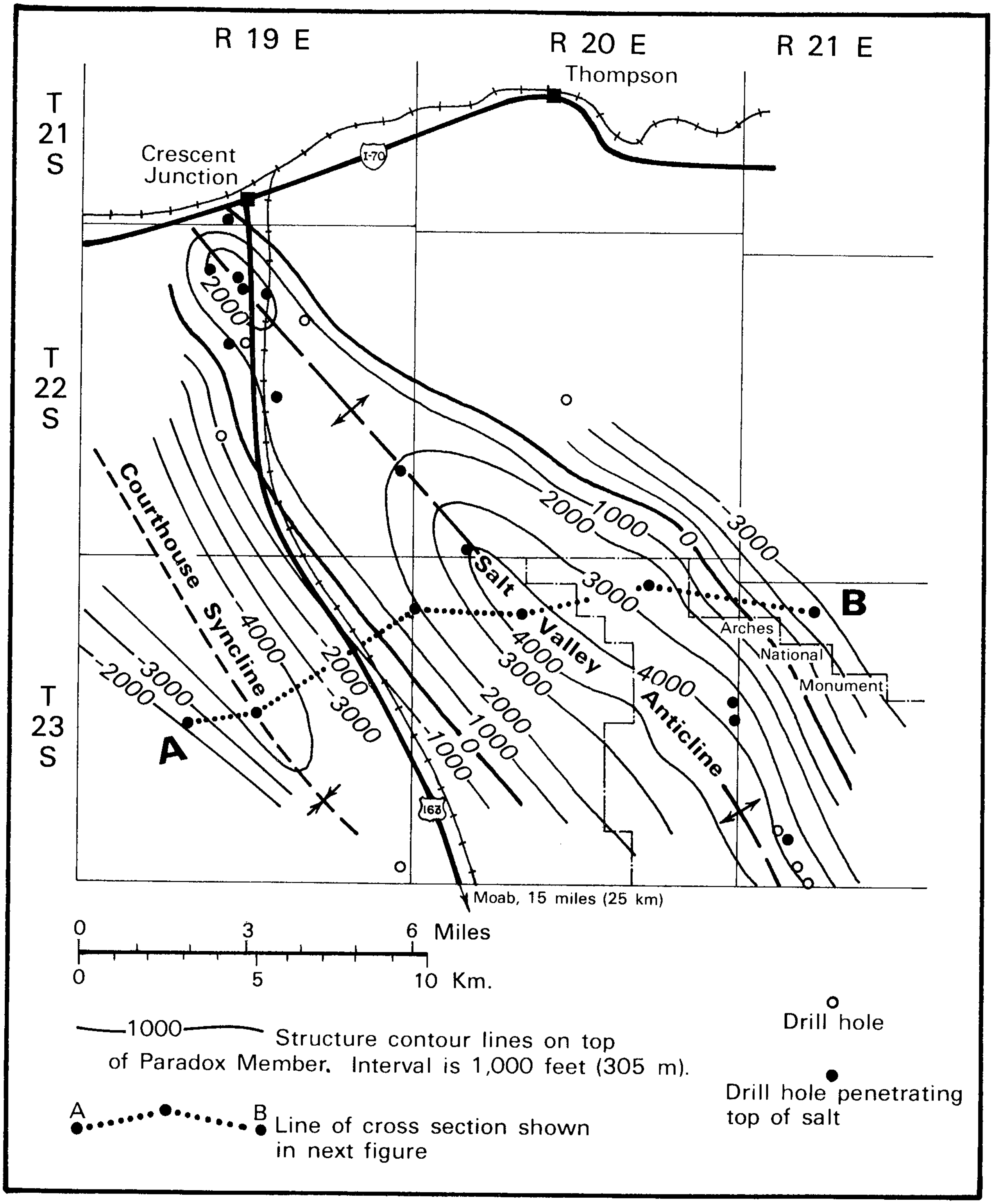
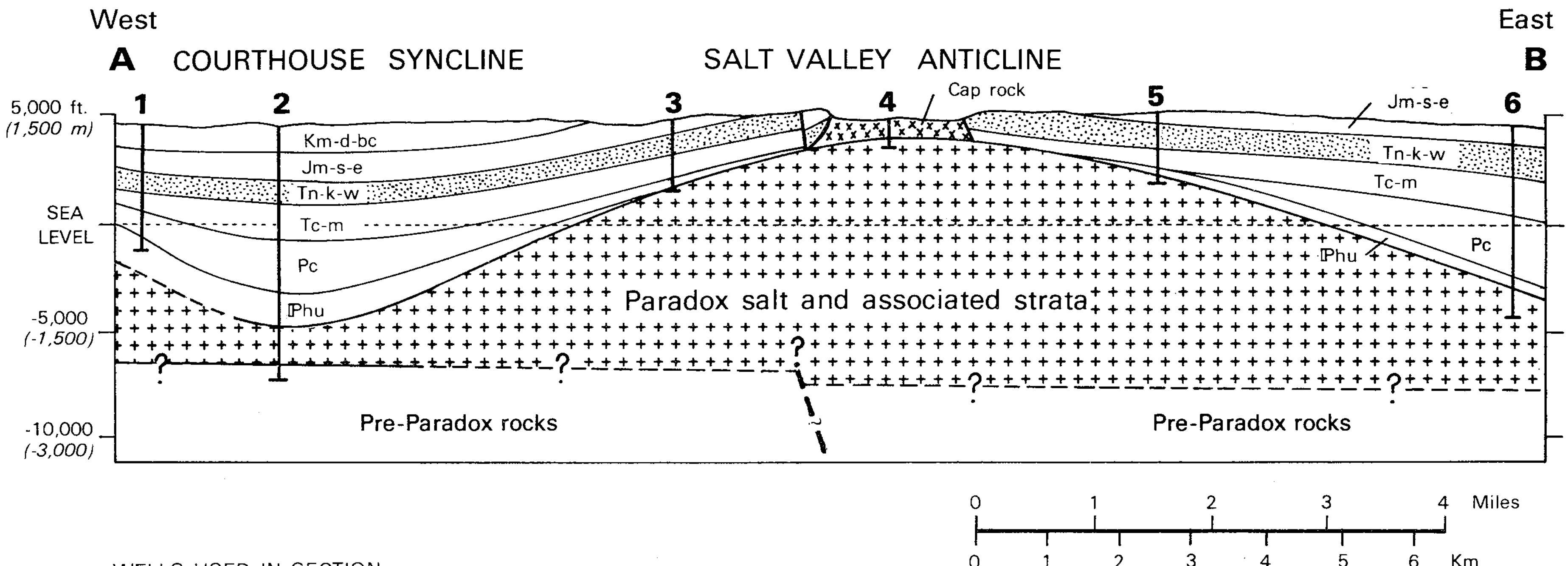


Figure 54. Structure-contour map on top of salt in Paradox Member of Hermosa Formation along Salt Valley anticline, Grand County, Utah (modified from Hite and Lohman, 1973).



WELLS USED IN SECTION

1. Equity, Donahue No. 1
2. Texaco, McKinnon No. 1
3. Continental, Gov't.—Hall No. 1
4. Western Allies
5. Pure, Salt Valley No. 1
6. Union, Devils Garden—USA No. 1

Km-d-bc	Mancos-Dakota-Buro Canyon
Jm-s-e	Morrison-Summerville-Entrada
Tn-k-w	Navajo-Kayenta-Wingate
Tc-m	Chinle-Moenkopi
Pc	Cutler
IPhu	Hermosa (Upper Member)

Figure 55. Cross section through Salt Valley anticline in Grand County, Utah (modified from Hite and Lohman, 1973). Line of cross section shown in previous figure.

synclinal valleys. The principal exceptions are the several large fresh-water springs in Paradox Valley that yield about 5,000 liters per minute (Hite and Lohman, 1973). Thcsc springs probably issue from faults present on the northeast side of the valley.

Ground Water

Data on ground water in the Paradox basin are limited, although Hite and Lohman (1973) summarized the general water-supply potential of Pennsylvanian and younger rock units. Principal bedrock aquifers, plus the Quaternary alluvium along rivers and major streams, supply many wells in the basin used for stock and domestic purposes, and a few wells are used for irrigation, municipal, and industrial supplies. Some of the wells located on the flanks or troughs of synclines between the salt anticlines yield water under artesian conditions.

Quaternary alluvium and terrace deposits are the principal source of good-quality ground water. Other aquifers that yield small supplies locally, where the structure is favorable, are the Dakota Sandstone, Salt Wash Member of Morrison Formation, Entrada Sandstone, Navajo Sandstone, and Wingate Sandstone (U.S. Geological Survey, 1964; Hite and Lohman, 1973). Other rock units overlying, or on the flanks of, the central cores of salt anticlines either are not water bearing or have not been tested.

Seismic Activity

The area underlain by salt in southeastern Utah and southwestern Colorado is free of recorded significant earthquake activity (fig. 15). In fact, no earthquake of Modified Mercalli Intensity V (MM V) or greater have been recorded in any part of the Paradox basin or the surrounding parts of the Colorado Plateau (Coffman and von Hake, 1973). The nearest recorded earthquakes outside the basin registered intensities of MM V and VI, while the Elsinore-Marysvale area of Utah, about 200 km west of Moab, is the nearest location experiencing quakes of MM VII or VIII.

The entire Paradox basin is within zone 1 (expected minor damage) on the seismic-risk map prepared by S. T. Algermissen (ESSA/Coast and Geodetic Survey, 1969) (fig. 16), and thus seismicity does not present any special problems related to waste storage in this area.

Mineral Resources

Oil and Gas

Principal production of petroleum comes from the southern part of the Paradox basin, outside the deep trough containing the salt anticlines. The famous Aneth field in this southern area produces oil from carbonate reefs developed in strata equivalent to the Paradox evaporites (Schneider and others, 1971; Molenaar, 1972), and the same is true for other smaller fields in the same general area.

Oil and/or gas has been produced from about 17 fields in the salt-anticline portion of the basin (Molenaar, 1972). Some of these fields are one-well fields, and some have already been depleted. Several of these fields produce oil from fractured shales interbedded with salt in the Paradox evaporites. Wells in these fields generally are completed at high flow rates, but the production rate declines rapidly due to the limited volume of such fracture reservoirs.

Some of the fields in the north part of the basin produce from the Mississippian Leadville Formation. The Lisbon field on the Lisbon anticline is the largest of these Mississippian producers. Production also is obtained from the Honaker Trail Formation (Pennsylvanian) and the Cutler Formation (Permian) at Andy's Mesa field on the flank of Gypsum Valley anticline.

The Paradox basin has relatively few oil and gas test holes, particularly in the northern part. New exploration in the basin will probably concentrate on searching for more stratigraphic traps in Devonian, Mississippian, Pennsylvanian, and Permian strata (Schneider and others, 1971). Most of this exploration in the northern part of the basin is expected to be centered on the flanks of the salt anticlines, away from the salt cores.

Salt

The vast salt resources of the Paradox basin are far from the current market areas, and thus they are not now being developed, nor are they expected to be produced on a large scale in the near future. No salt is being produced in the State of Colorado at the present time, and the Utah production is provided by four companies processing brine from Great Salt Lake in northwestern Utah (U.S. Bureau of Mines, 1972).

Because the salt resources of the Paradox basin are so great, and because the need to develop these resources in the foreseeable future is small, the storage of radioactive waste at one or several sites would undoubtedly make little to no impact on the future availability of salt resources from this region.

Potash

Deposits of potash minerals, chiefly sylvite and carnallite, are known in most of the northern two-thirds of the Paradox basin (Hite and Liming, 1972). Ten of the 29 evaporite cycles in the Paradox Member locally contain potash minerals, but at present most of these deposits have only marginal value. Potash is being developed now only on the Cane Creek anticline just west of Moab, Utah (Evans and Linn, 1970). Texas Gulf, Inc., began mining a potash bed at a depth of more than 800 m in 1964. The potash mine was flooded later and was converted to a solution-mining operation.

Recent studies by Hite (1977) show that the concentration of potash minerals in the Paradox Member is greatest in the northeastern part of the basin, which includes the Salt Valley anticline area, but the economic recoverability of these resources has not yet been proved (except on the Cane Creek anticline) owing to the complex geology and lack of adequate testing.

Other Minerals

Uranium and vanadium are produced chiefly from Triassic and Jurassic sedimentary rocks in the Paradox basin area (U.S. Geological Survey, 1964). Many operating and abandoned mines (most of them less than 100 m deep) dot the landscape, but the main potential host rocks have been eroded from the crestal areas of most salt anticlines. The chief uranium districts in the salt-anticline area are the Uravan and Big Indian districts.

Copper, lead, zinc, and other base and precious metals have been detected at numerous localities within the Paradox basin, and they are locally being produced from mines in both Utah and Colorado. These mines are typically away from the core areas of the salt anticlines. Gypsum resources in the cap rock are not highly prized, because generally they are impure and are intimately mixed with other rock types. Sand and gravel are locally obtained from open pits in alluvial and terrace deposits.

With the exception of gypsum, the distribution and occurrence of all these minerals are not related to the salt cores of the salt anticlines. Thus, there should be little or no conflict between underground storage of waste in a salt anticline and the continued exploration for and development of these mineral resources.

Regional Evaluation for Storage of Radioactive Waste

Geologic data summarized here indicate that Pennsylvanian salt deposits in the Paradox basin may locally be suitable host rocks for the underground storage of radioactive waste. The potential storage areas are mainly the salt anticlines in the northeast part of the basin, because in these structures the top of the salt is at a moderate depth below the land surface.

Salt anticlines contain a thick central core consisting mainly of rock salt. Although the nonsalt layers are locally gas bearing, the individual salt units are believed to be thick enough to isolate a storage facility from nonsalt strata. Inasmuch as the salt layers are commonly folded and distorted in the central cores, detailed knowledge of the geometry of salt units is needed to plan mining operations. The climate is arid, and desert-like conditions prevail in most parts of the basin. Land is sparsely populated, and much of the acreage is under government jurisdiction. No earthquakes of MM V or greater have been recorded in the salt region.

Relatively few oil and gas test holes have been drilled into the central cores of the salt anticlines, and the potential for future drilling and possible petroleum discovery lies on the flanks of the anticlines. There should exist little or no conflict between waste storage at one or two localities and continued development of oil and gas and other mineral resources in the basin. Potash is the only potentially useful resource intimately associated with salt in the salt anticlines, and further study is needed to assess the potential for future development of this potash.

In their discussion of the geology of salt anticlines in the Paradox basin, Hite and Lohman (1973) concluded that the Salt Valley anticline and the Shafer dome were deemed to be suited for further detailed investigation. These two structures appear most favorable because of the proximity of salt to the surface (200 to 500 m deep) and because the structure in thick salt units does not appear to be too complex. Both areas are on or near a railroad, are on public lands, and are remote from human activity. Studies of the Salt Valley area by Gard (1976) and Hite (1977) support the need for continuing investigation of this structure. It is also possible that other areas in the Paradox basin may later be deemed favorable, as more data become available from regional studies of the basin.

SUPAI SALT BASIN

Structure and Geologic Framework

A thick sequence of Permian salts is present at moderate depth in east-central Arizona (fig. 56). Marine evaporites here occur in the upper part of the Supai Formation, and thus the area is generally referred to as the Supai salt basin (also called the Holbrook basin in some reports). The salt deposits of the Supai basin were first described in detail by Peirce and Gerrard (1966), and subsequently Mytton (1973) discussed some aspects of the Supai salt basin as they relate to the storage of waste materials.

The Supai salt basin underlies about 6,000 sq. km in Navajo and Apache Counties, Arizona, and is located on the southern edge of the Colorado Plateau. Bounded by the Mogollon Rim on the south, by Black Mesa basin on the northwest, and by the Defiance uplift on the northeast, the basin contains sedimentary rocks that dip to the north and northeast at an angle of ½° to 1° and form a dip slope called the Mogollon Slope (fig. 57). Only about 750 to 1,350 m of sedimentary rocks overlie Precambrian rocks in the Supai salt basin.

The Lower Permian Supai Formation, the thickest unit in the area, consists of red sandstone, siltstone, and mudstone interbedded with anhydrite, gypsum, halite, and potash. The total thickness of the Supai Formation ranges from about 500 m near the Arizona–New Mexico state line to more than 800 m near Holbrook (Mytton, 1973). The Supai salt basin was a depositional basin during Early Permian time and represents the area of maximum thickening of Permian strata in Arizona. A thick sequence of interbedded evaporites and clastics was deposited in shallow-marine waters that entered the basin from the south and were intermittently cut off from the main body of sea water.

The Supai Formation has been subdivided in the subsurface into a lower and an upper member, separated by the Fort Apache Member (Peirce and Gerrard, 1966). Although some evaporites occur in the lower member and in the Fort Apache Member, the thickest accumulation of salt is developed in the upper part of the formation, which lies between the Fort Apache Member and the overlying Permian Coconino Sandstone. Further discussion of the Fort Apache Member is given by Gerrard (1966).

Overlying the Supai Formation in the salt area are the Permian Coconino Sandstone and Kaibab Formation. These in turn are overlain by the Triassic Moenkopi and Chinle Formations (figs. 57, 58).

The most prominent structural feature in the Supai salt basin is the Holbrook anticline (figs. 56, 57). Its axis has been mapped for more than 100 km by Bahr (1962). Strata on the north flank dip gently northward at an angle of about 2°. These same strata show a sharp reversal on the south flank, where the dip is typically less than 15° but locally as great as 50°. Bahr (1962) suggested that the Holbrook anticline may mark the present position of a regionally retreating salt-dissolution front and that the structure may not extend down below the salt beds. Other, smaller folds in the basin were mapped by Doeringsfeld and others (1958), Bahr (1962), and Peirce and others (1970).

Faults are scarce in the Supai salt basin. A few small faults of late Cenozoic age have been reported in Apache County (Akers, 1964), and a regional pattern of closely spaced faults and joints with northwest, north, and northeast trends was reported by Cooley (1963).

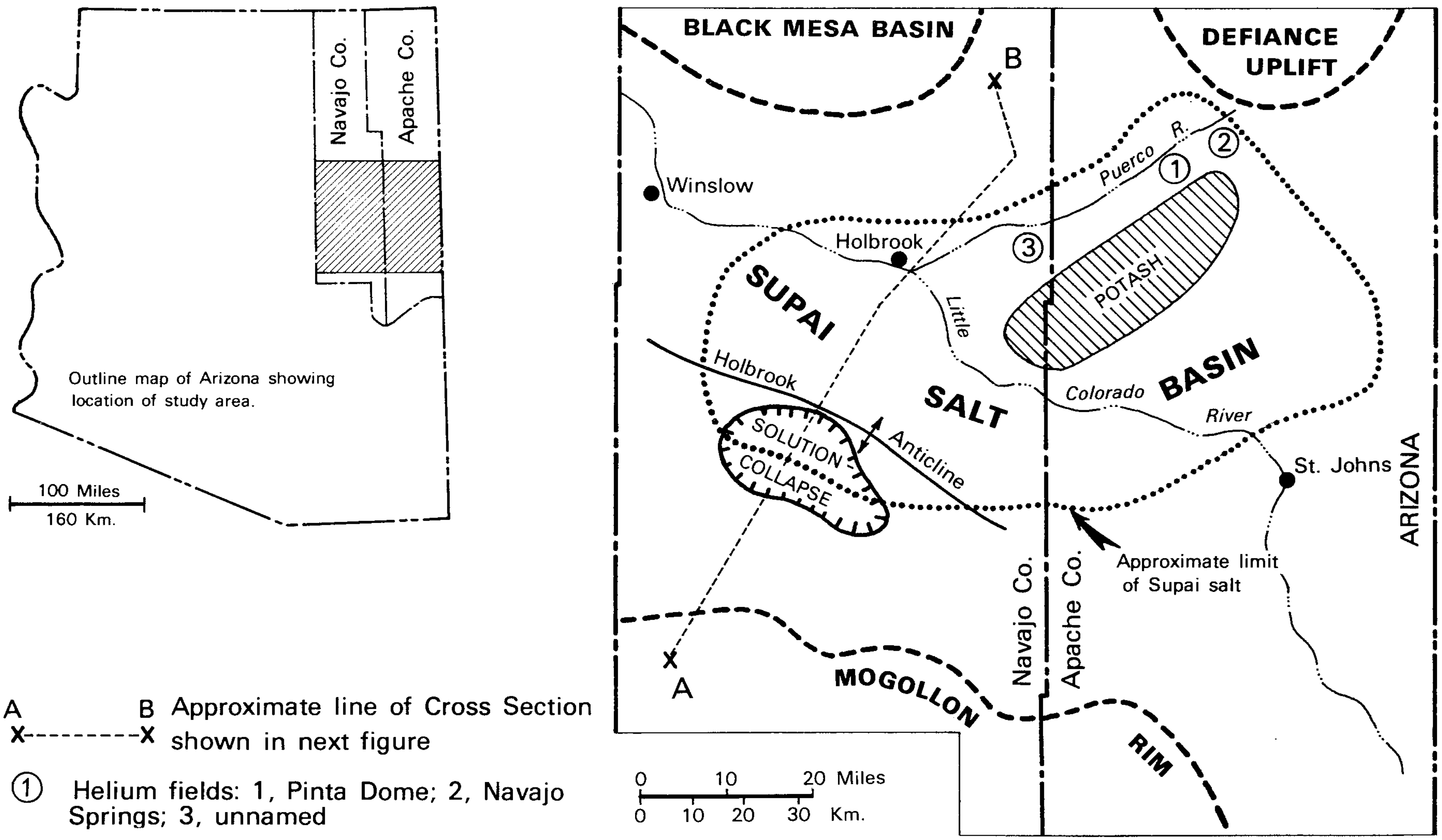


Figure 56. Index map of Supai salt basin and surrounding area showing structural features and mineral deposits of east-central Arizona (modified from Mytton, 1973).

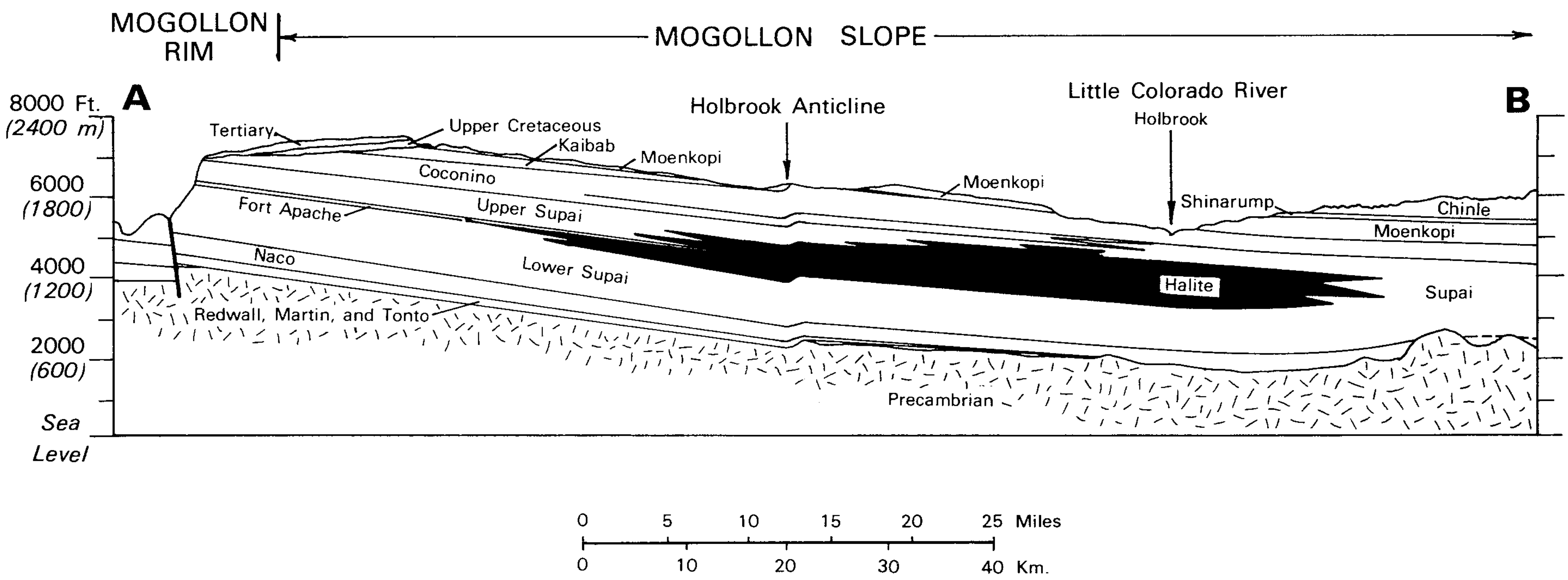


Figure 57. Generalized geologic cross section through Supai salt basin (modified from Brown and Lauth, 1958). Line of cross section shown in previous figure.

SYSTEM	SERIES	FORMATION	MEMBER
QUATERNARY*	HOLOCENE AND PLEISTOCENE		
TERTIARY*	PLIOCENE	BIDAHOCHI	
CRETACEOUS*	UPPER		
TRIASSIC*	UPPER	CHINLE	Petrified Forest
			Mesa Redondo
			Shinarump
	MIDDLE (?) AND LOWER	MOENKOPI	Holbrook
			Moqui
			Wupatki
PERMIAN	LEONARDIAN	KAIBAB* COCONINO	
	?	SUPAI	upper
	WOLFCAMPIAN		Ft. Apache
			lower
	?		
PENNSYLVANIAN		NACO	
MISSISSIPPIAN	MERAMECIAN-KINDERHOOKIAN	REDWALL	
DEVONIAN	UPPER	MARTIN	
CAMBRIAN	MIDDLE	TONTO	
PRECAMBRIAN		[*, not everywhere present]	

Figure 58. Stratigraphic nomenclature for Supai salt basin area (after Mytton, 1973).

Salt Deposits

Supai Formation

Rock-salt deposits in the Supai salt basin are confined to the Supai Formation, and, as noted, the thickest accumulation is in the upper member. The upper Supai consists of orange, red-brown, and gray sandstone and shale interbedded with limestone, dolomite, and evaporites (Peirce and Gerrard, 1966). Halite, gypsum, and anhydrite are the chief evaporites, although potash salts are rather widely distributed at one stratigraphic position.

The thickness of the upper Supai ranges from about 300 m around the perimeter of the salt basin to about 400 m near the center (fig. 59). The aggregate thickness of evaporite deposits in the basin ranges from 0 to 145 m, and the high halite/sulfate ratios coincide with areas of maximum evaporite accumulation (Peirce and Gerrard, 1966).

Based upon correlation of laterally persistent carbonate and sulfate units, Peirce and Gerrard (1966) subdivided the upper Supai into four zones, numbered I through IV, from bottom to top (figs. 60, 61). The clastic sediments and salt within these zones exhibit considerable lensing, suggesting frequent shifts to the site of evaporite deposition during Supai time. The total thickness of the evaporite-bearing sequence ranges from about 100 to 300 m (Mytton, 1973). The depth below ground level to the top of the evaporites ranges from about 180 to 750 m, with the greatest depths being in the northeastern part of the basin.

Salt units illustrated in the cross sections (figs. 60, 61) are not pure halite but consist of halite interbedded with anhydrite, siltstone, and claystone (Mytton, 1973). Individual layers of rock salt are commonly 3 to 6 m thick and locally reach more than 12 m. The only test holes drilled specifically to determine the nature and distribution of halite and associated minerals in the basin are those drilled for potash or for siting the underground hydrocarbon-storage facility near Adamana in the northern part of the basin. The main concentration of halite appears to be in an interval 120 m thick in the upper half of the evaporite sequence along a northeast-trending belt in the center and northeast parts of the basin (Peirce, 1969).

Salt Dissolution

Dissolution of salt has been described only in the southwest part of the Supai basin, just south of the Holbrook anticline (figs. 56, 59). Abundant sinkholes and related dissolution-collapse structures in the area have produced a typical karst topography, and a study of aerial photographs taken in 1936 and 1953 shows that numerous deep sinks developed during that period. Thus, salt dissolution at depth clearly has had a continuing influence on the area in recent years (Bahr, 1962).

Evaporite rocks (halite and anhydrite) in the southwest area probably attained a depositional thickness of 200 m, but this has been reduced considerably by dissolution (Bahr, 1962). Strong evidence of this is seen in comparing the salts in drillhole 10 with those in drillholes 3 and 11 (fig. 60). Salt dissolution has probably been aided by percolation of ground water from the overlying Coconino Sandstone, the major aquifer in the region.

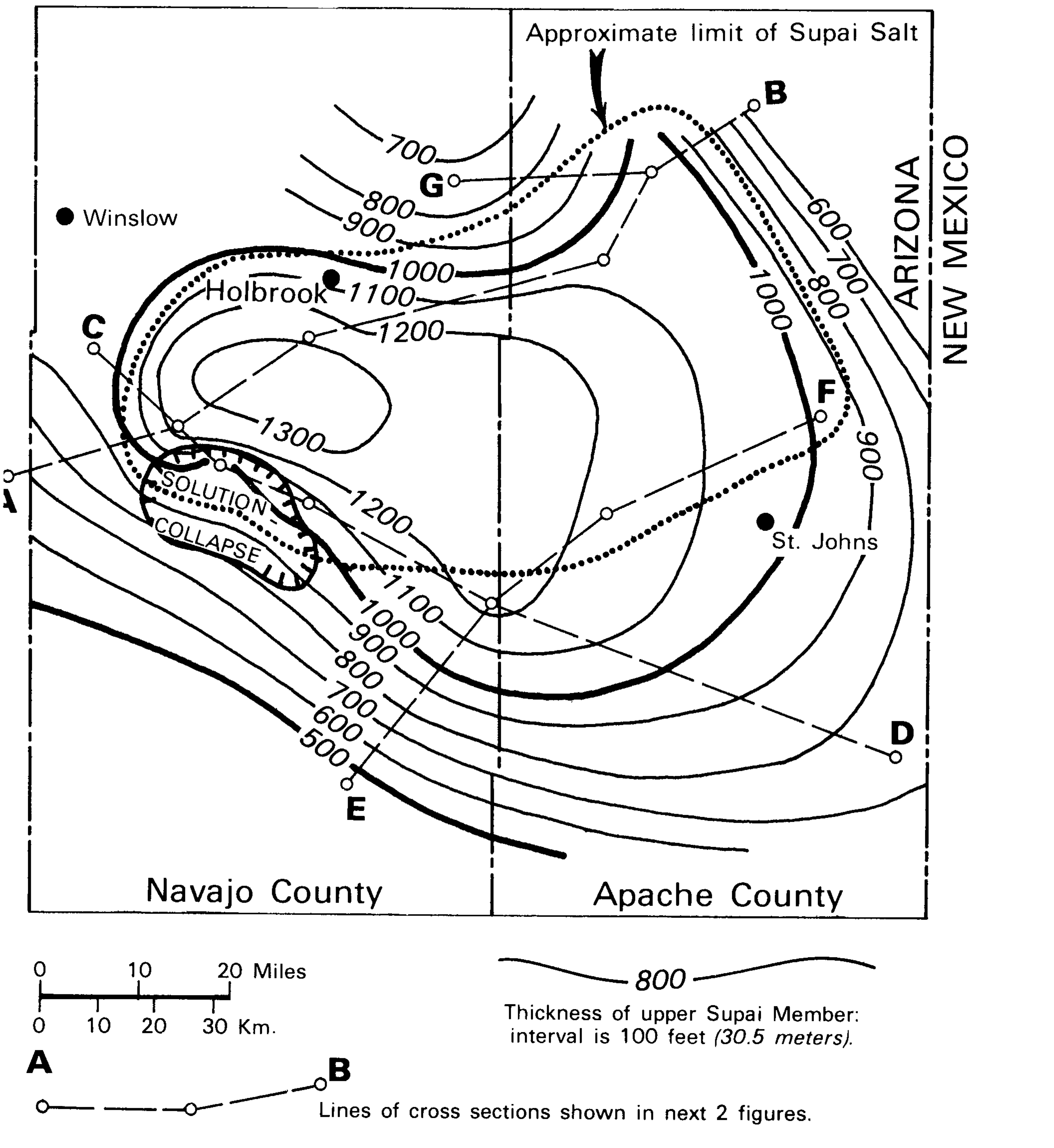


Figure 59. Thickness in feet of upper member of Supai Formation, and location of cross sections in Supai salt basin (modified from Peirce and Gerrard, 1966).

Hydrology

Surface Water

The major drainage system in the Supai salt basin is the Little Colorado River, which flows northwest past Holbrook and on to the Colorado River (fig. 56). The principal tributary to the Little Colorado River is the Puerco River. The average annual precipitation in the area is about 20 to 30 cm, and the average annual runoff ranges from less than 0.2 cm in most parts of the basin to as much as 13 cm at higher elevations along the Mogollon Rim (Ligner and others, 1969). In the upper reaches of the principal rivers, the available streamflow is used extensively for irrigation.

Ground Water

The major aquifer in the area is the Permian Coconino Sandstone, which in some areas forms a multiple-aquifer system with the Kaibab Limestone and the uppermost strata in the Supai Formation (Cooley, 1963; Akers, 1964). The base of this aquifer system is 30 to 60 m above the top of the salts in parts of the basin. These aquifers are recharged mainly near the Mogollon Rim and the White Mountains, and ground water moves northward along the Mogollon Slope. Ground water occurs under artesian conditions in much of the area. Minor amounts of water are withdrawn from Triassic and Tertiary rocks and from alluvium along the principal rivers.

Fracturing of sedimentary rocks owing to joints and faults has enhanced the occurrence, yield, and movement of ground water in the area (Cooley, 1963). The yield of some wells is as much as 3,800 liters per minute.

The quality of water from the Coconino Sandstone is generally good, even though the total dissolved solids in this aquifer range from 133 to 2,500 ppm in most areas (Cooley, 1963).

All fresh-water aquifers in the basin are stratigraphically above the salt deposits. However, inasmuch as the base of the aquifer system is locally within 30 to 60 m of the salts, additional detailed studies are especially needed for evaluation of the basin geohydrology.

Seismic Activity

The Supai salt basin has not had any recorded earthquakes with a Modified Mercalli Intensity V (MM V) or greater (Coffman and von Hake, 1973). The only earthquake near the basin was an event of MM VI that occurred about 40 km to the north in 1950 (see fig. 15). The next closest seismic events were near Flagstaff, Arizona, about 140 km west of Holbrook, where several earthquakes of intensities MM V through MM VII were recorded.

All of the Supai salt basin lies within zone 2 (expected moderate damage) on the seismic-risk map of S. T. Algermissen (ESSA/Coast and Geodetic Survey, 1969) (fig. 16).

Mineral Resources

Oil and Gas

Petroleum production in Arizona is small compared to most other states. Oil and gas tests have been drilled in the Supai salt basin area, but so far only helium has been found

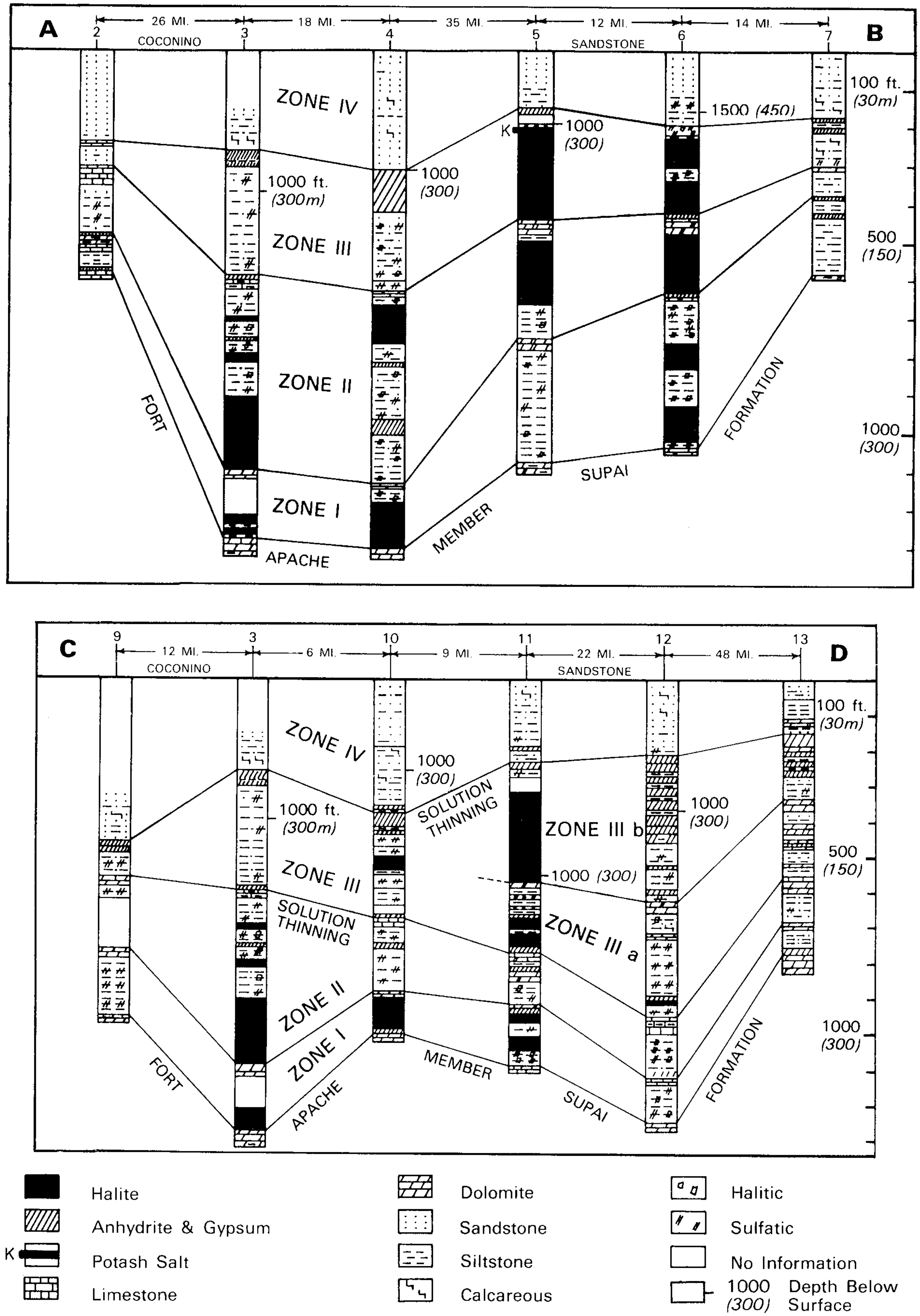


Figure 60. Stratigraphic cross sections (*A-B* and *C-D*) of upper member of Supai Formation (modified from Peirce and Gerrard, 1966). Lines of cross sections shown in preceding figure.

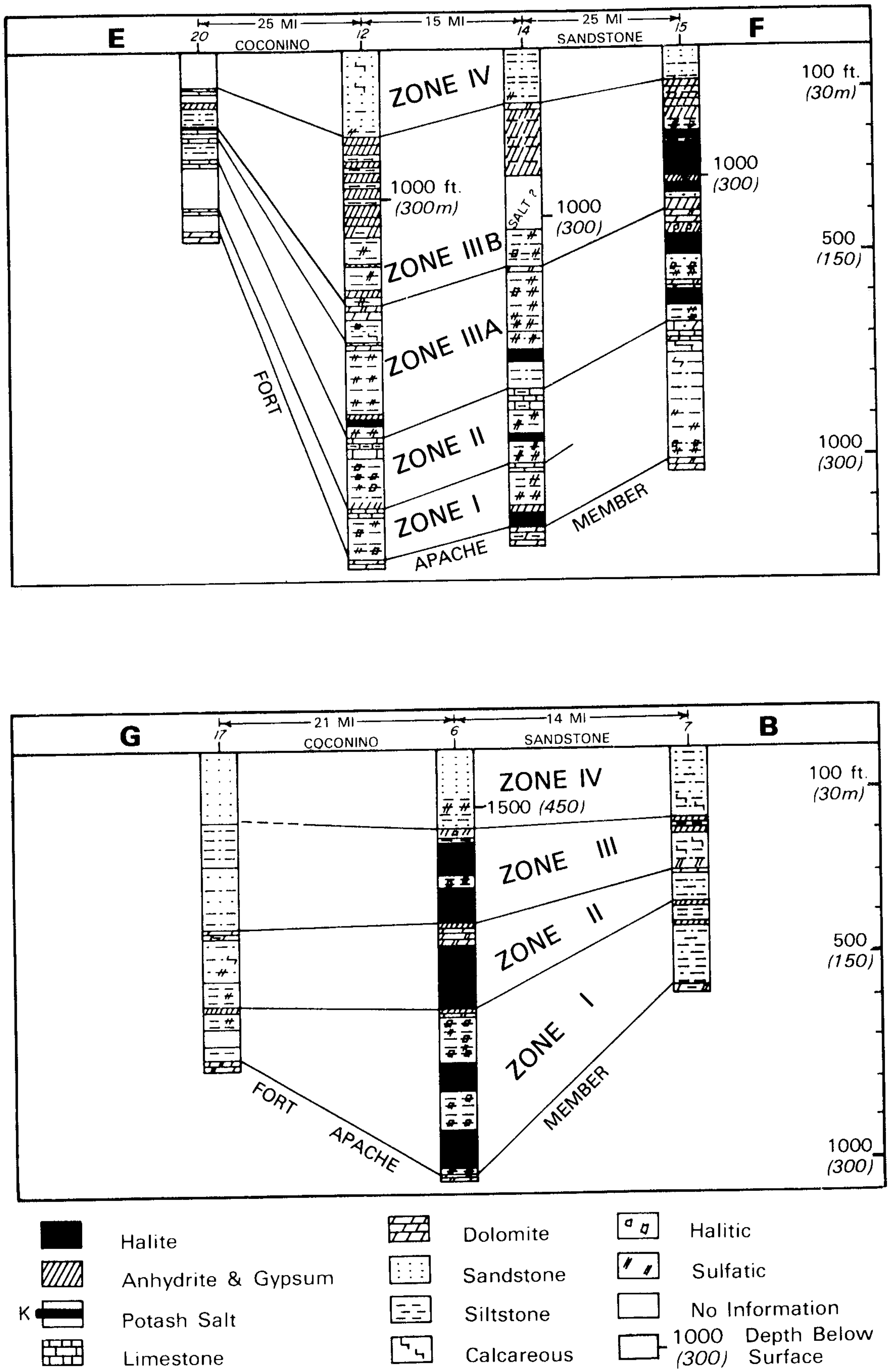


Figure 61. Stratigraphic cross sections (*E-F* and *G-B*) of upper member of Supai Formation (modified from Peirce and Gerrard, 1966).

in commercial quantities. Oil and gas discoveries in the state have been limited to the far northeast, in an area of northern Apache County. Reservoirs include sedimentary rocks of Pennsylvanian, Mississippian, and Devonian age, and, at the prolific Dineh-bi-Keyah field, production is from porous igneous rock of Tertiary age that was intruded as a sill into Pennsylvanian marine strata (Peirce and others, 1970). Although petroleum has not yet been discovered in the Supai salt basin, exploration is still being carried out, particularly along and south of the Holbrook anticline, and more recently within the southeastern sector of the basin.

Helium

Helium is produced in the northern part of the Supai salt basin (fig. 56) from the Coconino Sandstone of Permian age and the Shinarump Member of the Chinle Formation of Triassic age (O'Sullivan, 1969). The largest helium-producing field in the state is the Pinta Dome field, which yields about 8.5 percent helium in a nitrogen-rich gas from a depth of about 300 m. Gas at the Navajo Springs field contains 8.2 percent helium, and gas at an unnamed field in Navajo County contains 5.1 percent helium. Large reserves of helium remain in these fields (O'Sullivan, 1969), and there exists the possibility that additional helium will be discovered in areas close to the Defiance uplift.

Salt

The quantity and quality of salt in the Supai basin are poorly known, and it is difficult to assess the reserves or the potential for developing this resource. No salt mining has occurred in the basin to date. The only current use of salt is the underground hydrocarbon-storage facility operated by Williams Energy Co. near Adamana along the north edge of the basin. Storage space at Adamana was created by forming several solution caverns about 300 m below the surface in the upper part of the salt sequence.

Storage of radioactive waste at one or several sites in the Supai basin would not exert an adverse impact on the future availability of salt resources in the region.

Potash

Sylvite, a potash mineral, is mixed with halite in zone III of the upper member of the Supai Formation (fig. 60). This occurrence was discovered in 1958, and, since then, approximately 100 exploration holes have been drilled to evaluate the deposit (Peirce, 1969). Potash underlies about 750 sq. km in Apache and Navajo Counties (fig. 56), but the companies evaluating this resource have not released details on grade or thickness. The deposit apparently is irregular, and its top ranges from 200 to 600 m below the surface.

Exploration has decreased since the late 1960's, suggesting that the potash deposit may not justify development under economics prevailing at the present time (Peirce, personal communication, 1976). Selection of a waste-storage site in or near this district must be preceded by a study of the potential use of this resource.

Other Minerals

Other important rocks and minerals are not known to be present in commercial quantities within the Supai salt basin area, except for sand and gravel, which is being recovered only locally.

Regional Evaluation for Storage of Radioactive Waste

Geologic data on the character, thickness, and lateral continuity of salt beds in the Supai salt basin are limited, but enough data exist to suggest that there are areas, chiefly in the central part of the basin, where layers of rock salt at least 6 to 12 m thick are 300 to 750 m below the surface; they may be suitable locally for waste storage. The total thickness of the salt-bearing sequence ranges from 100 to 300 m. The salt deposits have not been folded, faulted, or otherwise deformed, except along and south of the Holbrook anticline, and although no significant seismic activity has been recorded in the basin, it is in seismic-risk zone 2 (expected moderate damage). The solution-collapse area southwest of the Holbrook anticline needs to be studied further owing to its relation to salt dissolution.

The climate of the region is arid, and desert-like conditions prevail. The land is sparsely populated, and a small segment of the north-central part of the basin is included in the Petrified Forest National Monument.

Relatively few oil and gas tests have been drilled in the basin, although a number of boreholes were drilled to examine the potash deposits. Potash and helium are the only minerals that appear to have the potential for commercial production in the foreseeable future, and both of these commodities are known only in the north-central and northeastern parts of the basin. The same applies to the only other competitive use of the salt sequence at the present time, the underground hydrocarbon-storage facility near Adamana. Any potential waste-storage area should be examined for potash and helium in particular.

Additional detailed geologic and hydrologic data are clearly needed to fully evaluate the potential of the Supai salt basin. The salt-bearing rocks of the basin are overlain by the major aquifer of the region, the Coconino Sandstone, and the relationships between the salt and this aquifer require close examination.

OTHER SALT DEPOSITS

In addition to the 6 salt basins previously discussed in detail, there are 13 other basins or provinces in the United States where rock salt has been reported (fig. 1). Eleven of these salt occurrences are in the western part of the country (figs. 62, 63), and the other two are in the southeast. The size of these deposits is generally smaller than those discussed earlier; at least, those parts of the deposits at moderate depths are generally smaller. Although the suitability of these other salt deposits for radioactive-waste storage has not been examined closely, some of the deposits may be found suitable after further study of existing data and if additional borehole data can be acquired. In a preliminary evaluation of these salts for waste storage, each of these 13 deposits can be grouped into 5 general classes:

1. Thick salts at moderate depth. Included in this group of salts are the Luke basin, Red Lake basin, Virgin Valley, and Eagle Valley deposits as well as parts of the Sevier Valley, Williston basin, and Northern Denver basin.
2. Thick salts at depths now generally considered too great for underground mining. This includes the Powder River basin; most of the Sevier Valley, Williston basin, and Northern Denver basin; and the Utah portion of the Idaho-Utah-Wyoming deposit.
3. Salts that appear to be impure and are structurally complex. Parts of these deposits are at shallow depth, and they generally are of limited extent. This group includes salts at Saltville and in the northern part of the Idaho-Utah-Wyoming deposit.
4. Thin salts at moderate depth that are closely associated with important mineral deposits of oil shale, trona, nahcolite, and dawsonite. The Piceance and Green River basins are in this group.
5. Salt beds that are thin and at great depths. The southern Florida deposit alone is in this category.

Luke Basin (Arizona)

The Luke basin in central Arizona (fig. 62) contains a thick sequence of rock salt (halite) and shale interbeds at shallow depth (fig. 64). The salt body is near Luke Air Force Base, about 25 km west of Phoenix, in Maricopa County, and is believed to underlie little more than 100 sq. km and to extend from less than 300 m below the surface to a total depth of perhaps 2,000 m. Data presented here on the Luke basin salt are summarized from work by Eaton and others (1972), Mytton (1973), and Peirce (1974, 1976).

An exploratory test hole drilled just east of Luke Air Force Base penetrated about 1,085 m of halite without reaching the base of the salt. The top of the salt is about 265 m deep in this borehole. A generalized lithologic log of this test hole, based on an interpretation of gamma ray-neutron logs by R. J. Hite of the U.S. Geological Survey, was presented by Mytton (1973), as follows: (1) top 245 m not described, (2) 20 m of anhydrite cap rock, (3) 150 m of halite with shale interbeds 0.6 to 2.4 m thick, (4) 180 m of argillaceous halite, (5) 150 m of halite alternating with argillaceous halite, (6) 400 m of halite with shale interbeds 0.3 to 2 m thick, (7) 60 m of halite, (8) 30 m of halite alternating with argillaceous halite, and (9) nearly 115 m of halite with sparse shale interbeds 0.3 to 2 m thick. Several other boreholes have been drilled into the top of the salt, but only a few meters of core has been taken.

Boundaries and depths of the Luke basin salt mass (fig. 64) are based largely upon geophysical interpretation of gravity data. Salt in the Luke basin is confined, at least in its

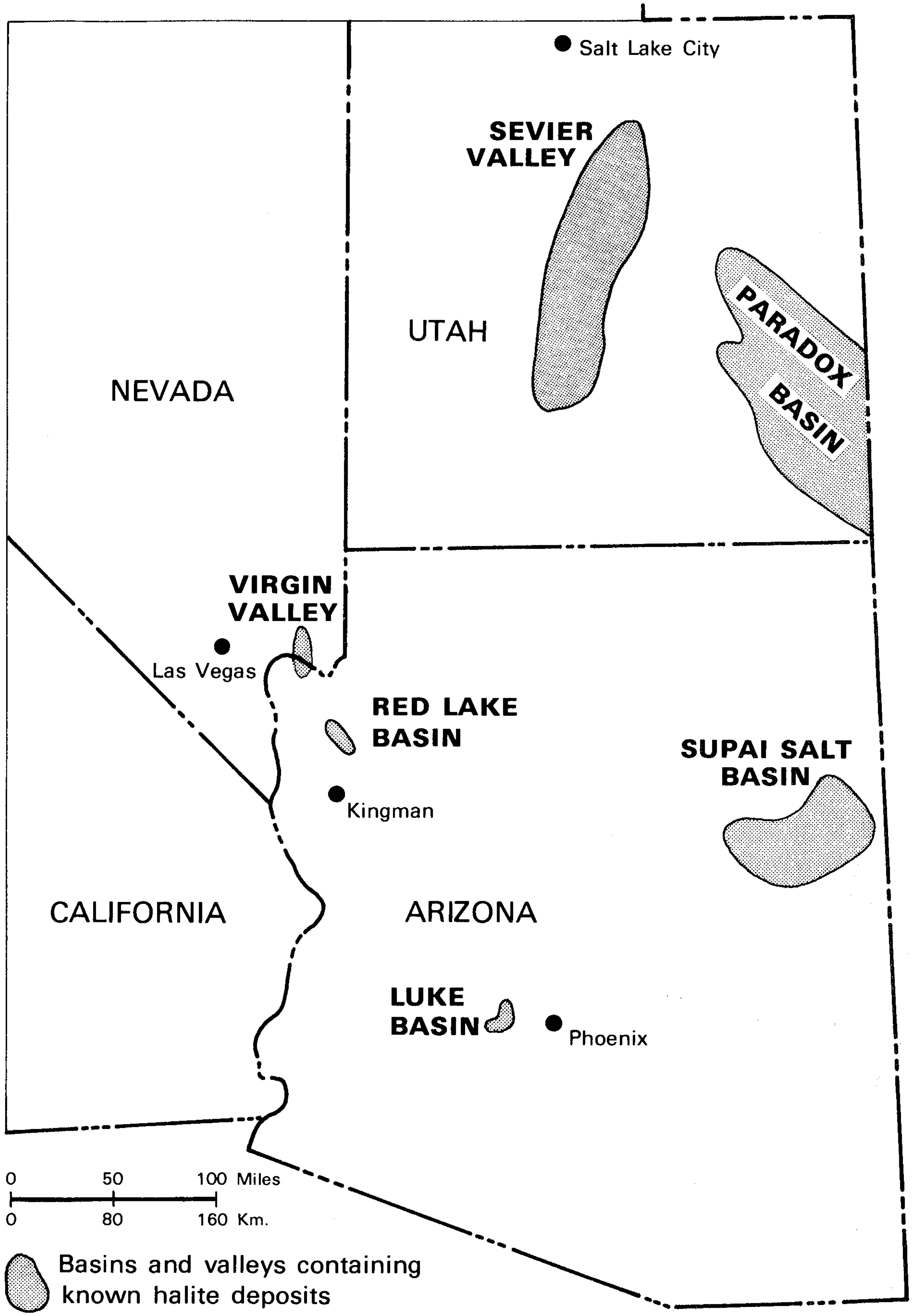


Figure 62. Map showing location of salt deposits in southwestern United States.

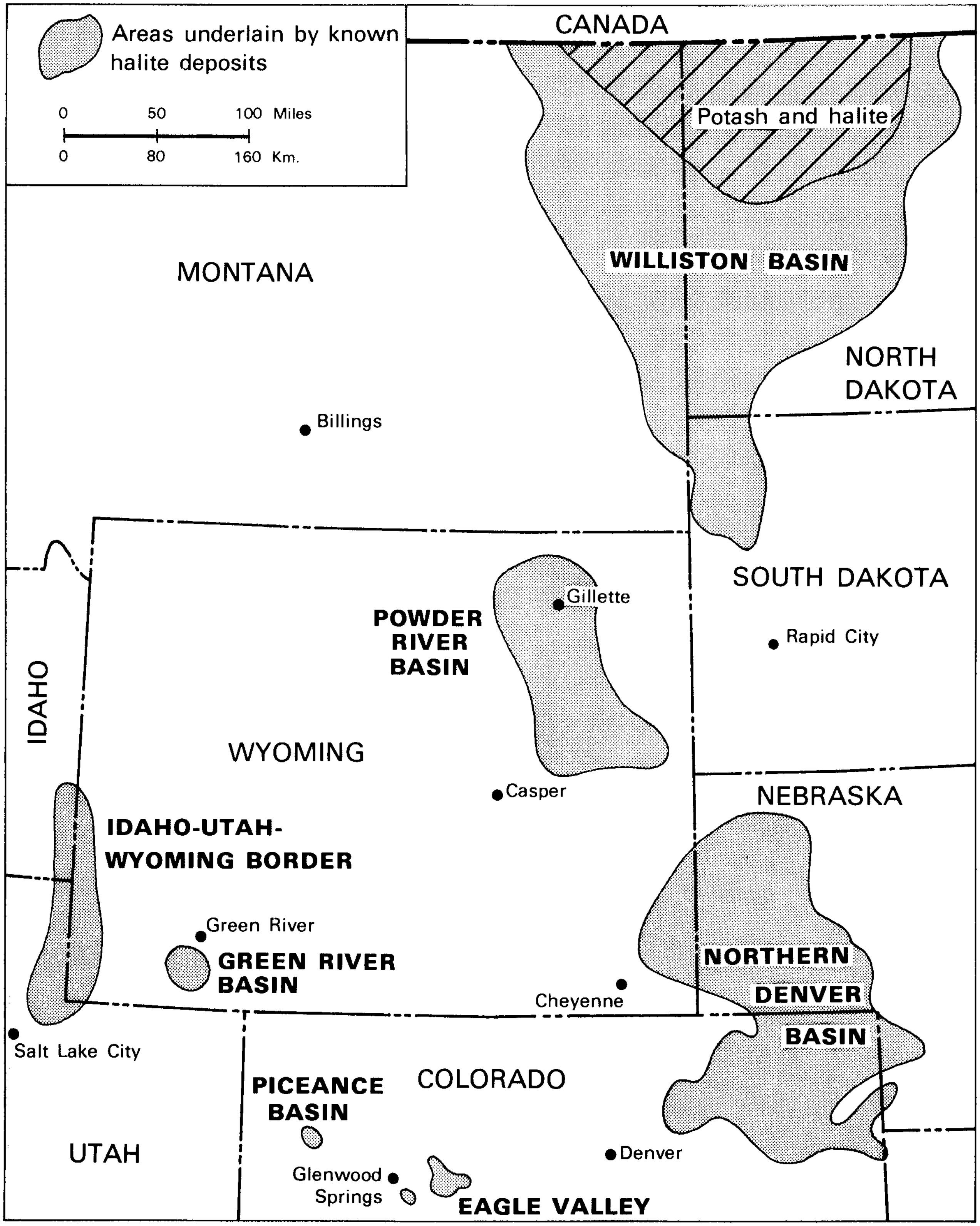


Figure 63. Map showing location of salt deposits in northwestern United States.

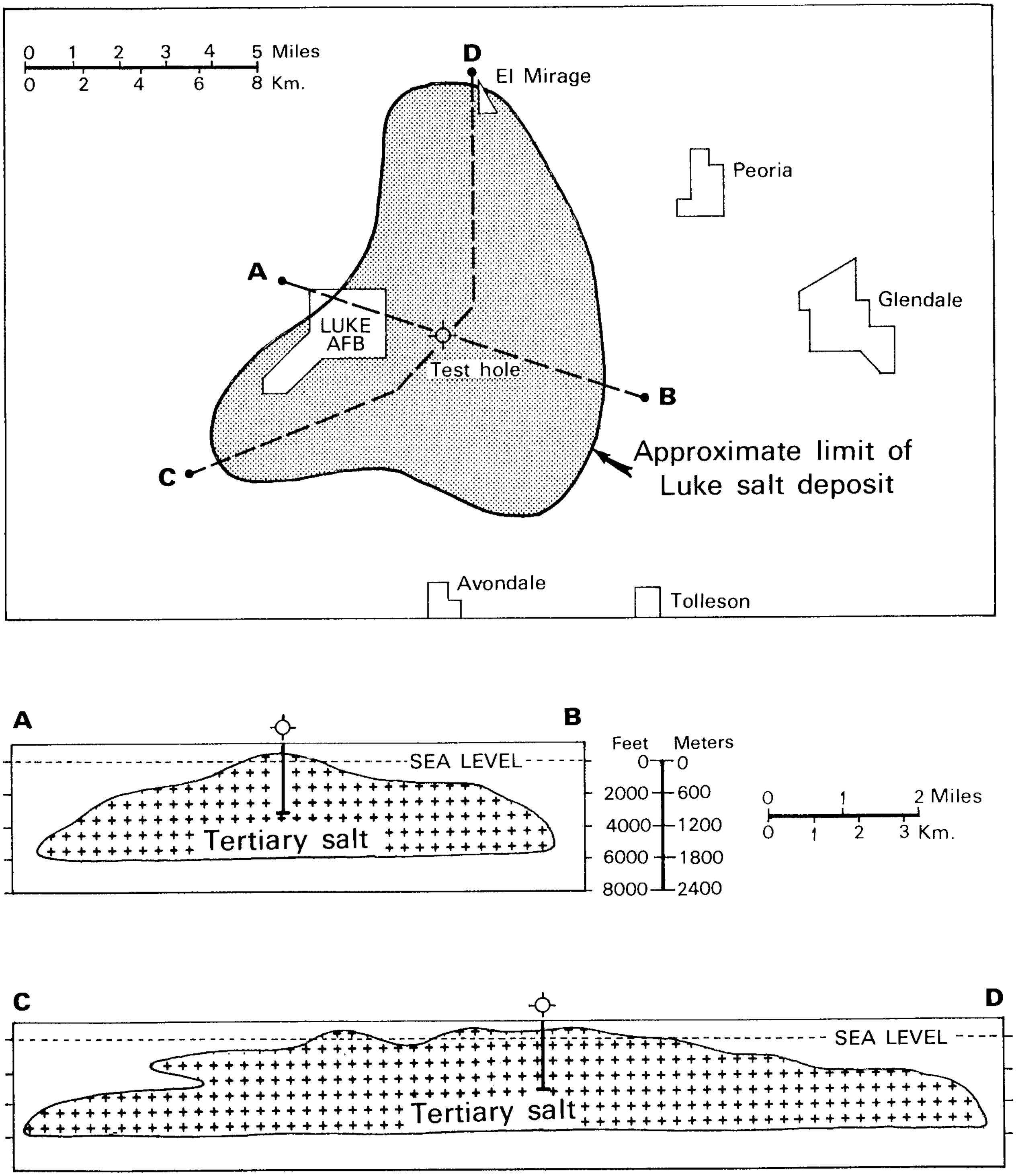


Figure 64. Map and cross sections showing generalized geophysical interpretation of Luke basin salt deposit west of Phoenix, Arizona (modified from Eaton and others, 1972).

upper part, by Late Tertiary fine-grained clastic sediments. The deposit apparently was formed in a long-standing saline lake that existed during part of the Miocene Epoch. Contact relationships between the salt and surrounding clastics are not yet clear, so there is uncertainty whether the salt may have flowed and caused diapirism. The collapse of casing in several water wells and the presence of several open fissures in alluvium above the salt suggest that the salt may be rising and doming the overlying sediments (Eaton and others, 1972).

Ground water in the shallow valley fill around the salt deposit is generally of good quality, but above the high part of the salt mass the water is brackish to saline, ranging erratically in salinity from 500 to more than 9,000 mg/l. The Luke basin is in a desert-like environment, with precipitation averaging between 12 and 25 cm per year.

The presence of a thick sequence of salt at moderate depth appears attractive for the possible storage of radioactive waste, but much additional geologic and hydrologic data are needed to evaluate this basin. The complete structure, physical extent, and detailed lithology of the Luke basin salt mass are still matters of conjecture. Development in this deposit of a hydrocarbon-storage facility (propane) by the CAL GAS Co. in conjunction with the Southwest Salt Co. of Phoenix (this firm purchases the brine from the cavern excavation) is expected to reach a capacity of 340 million liters in a few years (Peirce, 1977, personal communication). At present, this represents the only use being made of the salt mass.

Red Lake Basin (Arizona)

The Red Lake basin in northwestern Arizona contains a thick mass of rock salt (halite) at shallow depth (fig. 65). It is located beneath the northwest-trending Hualpai Valley, about 45 km north of Kingman in Mohave County. About 1,200 m of salt was drilled in one borehole, and the base of the salt was not reached. Geophysical work, principally gravity data, indicates that the mass of salt might extend about 20 km along the length of Hualpai Valley, about 8 km perpendicular to the sides of the valley, and might be as thick as 3,000 m (fig. 65). These data, and other observations that follow, are largely from reports by Peirce (1972, 1974, 1976).

Direct information about the salt in the Red Lake basin comes from only three boreholes. The Kerr-McGee Corp. drilled two tests near Red Lake Playa in 1958. The deeper test encountered salt about 450 m below the surface and then cored 360 m of coarsely crystalline halite without reaching the base. Later, in 1970, El Paso Natural Gas Co. drilled about 1,200 m of halite after encountering the top of the salt at a depth of 540 m.

The model presented by Peirce (1972, 1974, 1976) is that of rapidly accumulating nonmarine halite in a rapidly subsiding, closed basin. The salt and enclosing sediments are thought to be late Tertiary (Miocene) in age. Contact relationships between the salt and fine-grained valley fill have not yet been delineated, so whether the salt may have flowed and caused diapirism remains an uncertainty.

Data on ground water in this remote, sparsely populated area are not available. The climate is desert-like, with an average annual precipitation of 12 to 25 cm.

A thick sequence of salt at moderate depth exhibits some measure of interest for the storage of radioactive waste, but much additional geologic and hydrologic data are needed to evaluate the Red Lake basin. Principal uncertainties that will require further study are the structure, the physical extent, and the detailed lithology of the salt mass.

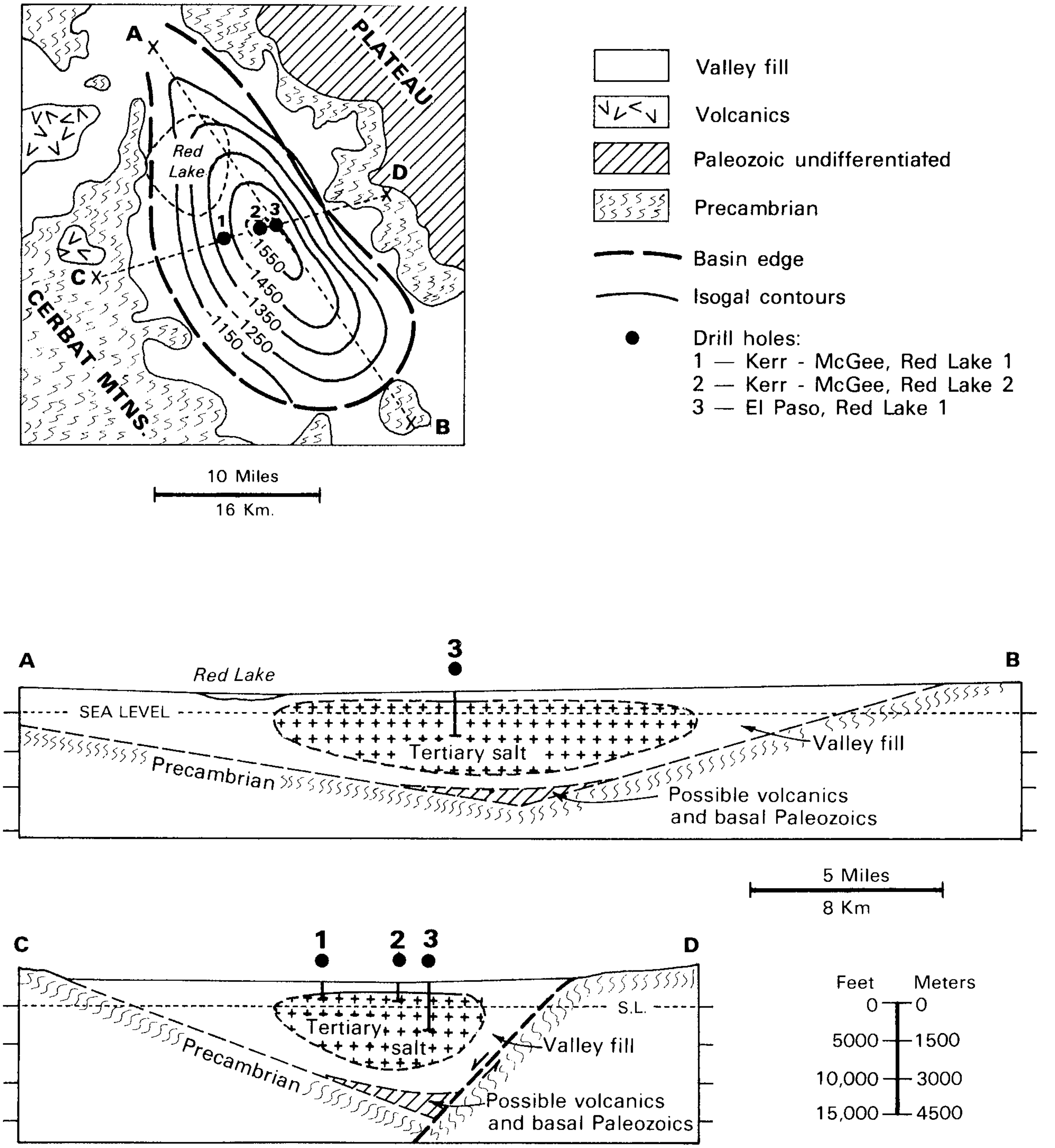


Figure 65. Generalized geologic map and cross sections showing salt in Red Lake basin of northwestern Arizona (modified from Peirce, 1972).

Virgin Valley (Nevada-Arizona)

The Virgin Valley salt is a thick unit of halite occurring at shallow depth in the Virgin Valley-Detrital Valley trough in Clark County, southeastern Nevada, and Mohave County, northwestern Arizona (fig. 66). In Nevada, much of the salt deposit lies beneath Lake Mead, and all of it appears to be within the Lake Mead Recreation Area, administered by the National Park Service.

Exposures of rock salt and salty soil along the course of the Virgin River were described by Longwell (1928) before Lake Mead was formed, and subsequent reports by Pierce and Rich (1962) and, especially, Mannion (1963) emphasize the geology of the salt deposits in the subsurface. Longwell and others (1965) described the geology and mineral deposits of Clark County. The general suitability of these salts for possible storage of radioactive waste was summarized by Netherland, Sewell and Associates (1977). Exposure of rock salt at the surface is possible because of the desert-like climate; average annual precipitation is only 12 to 25 cm.

Salt occurs in the lower part of the Muddy Creek Formation of Late Tertiary (Pliocene?) age. The formation originated as playa, lake, and fluviatile sediments (sand, silt, and clay), with the salt deposited in saline lakes.

The salt has been penetrated in several boreholes drilled in Nevada. Of the 3 tests described by Mannion (1963), only 1 entirely penetrated the salt. Test 1 encountered halite from 620 to 915 m, and test 2 encountered halite from 560 to 1,100 m; both holes bottomed in salt. Test 3 drilled into the halite at 260 m and passed out of it at 610 m. Detailed descriptions of these cores were presented by Netherland, Sewell and Associates (1977).

Halite within the salt body is coarsely crystalline, generally brownish gray, and contains only sparse indications of bedding (Mannion, 1963). Salt crystals commonly are 0.6 to 1.2 cm in diameter. The principal evidence of stratification is shown by layers of glauberite, clay, and tuff. Some of these layers are distorted, and a few are completely disrupted, apparently owing to recrystallization of the salt. Stratigraphically below the top 120 m of salt, the overall composition is about 93 percent halite. Principal impurities are grains, blebs, and interstitial masses of light-brown sand, silt, and glauberite between and within the salt crystals. Glauberite is an abundant and ubiquitous component of the salt unit, probably averaging more than 3 percent of the total deposit.

The salt and adjacent rocks are locally folded and faulted, and upward movement of salt is also indicated by the domal bulges in which salt is or was exposed (Mannion, 1963). In one drillhole, salt was strained, shattered, and crushed at depths below 870 m. Some salt showed faults, slickensides, and sheared textures.

Evidently some movement has occurred in the deeper parts of the salt mass, but core recovery was too poor to permit even an estimate of the extent of disturbance (Mannion, 1963). The presence of unhealed fractures indicates that stresses acted too quickly and too recently for the salt to recrystallize within the seemingly dry salt body. Movement along faults of the Las Vegas shear zone, which passes about 30 km southwest of the salt mass, occurred as recently as 10,000 years ago, and there is evidence that the fault on the west side of Virgin Valley has been active during Holocene time, almost to the present (Netherland, Sewell and Associates, 1977).

Several boreholes put down in the Detrital Valley area of northwestern Arizona encountered salt at a depth of 125 to 180 m (Pierce and Rich, 1962). The salt here is 150 to 210 m thick, has few impurities, and is largely recrystallized. Based on drilling, the salt is

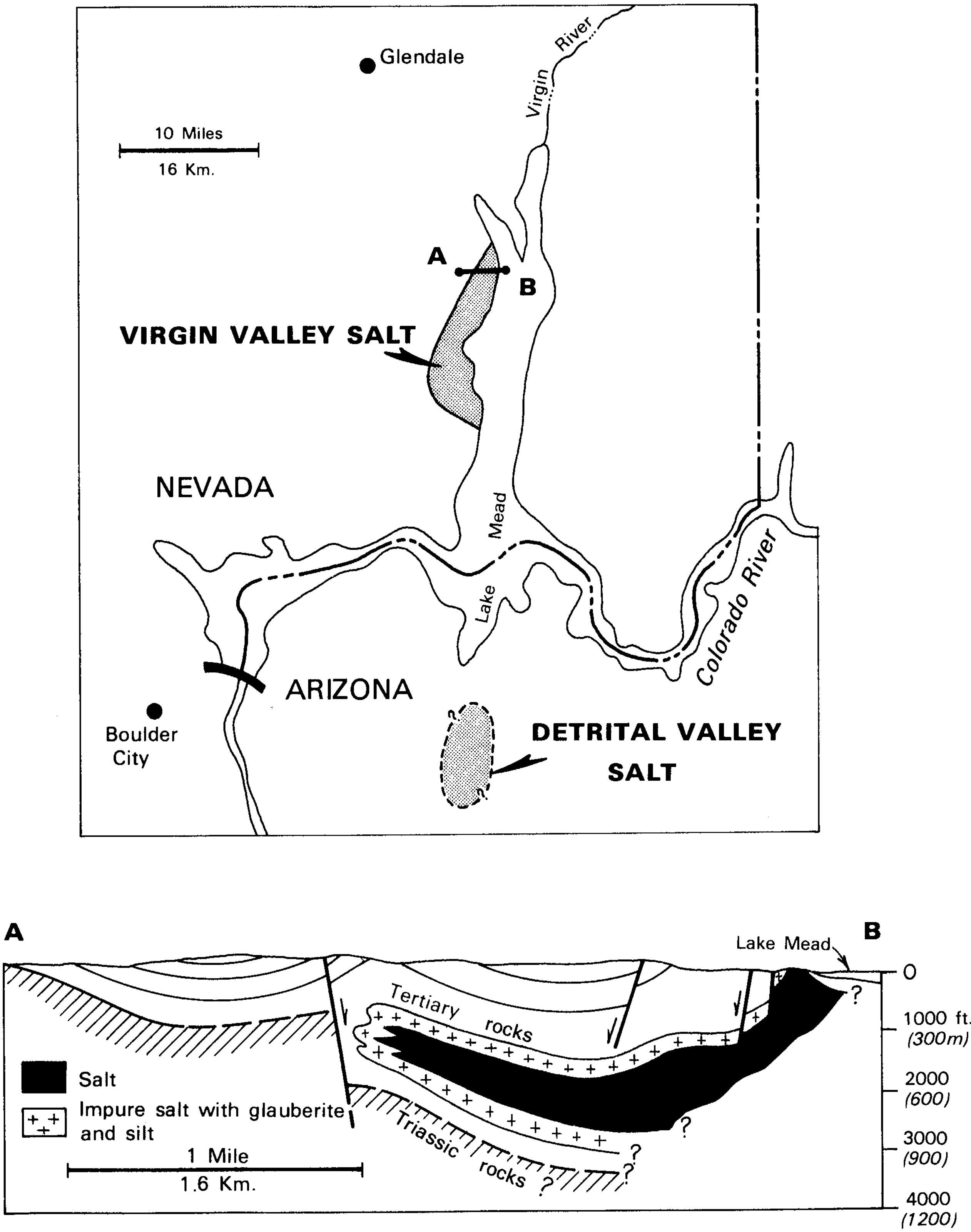


Figure 66. Generalized map and cross section showing Virgin Valley-Detrital Valley salts in southeastern Nevada and northwestern Arizona (modified from Mannion, 1963).

known to extend over more than several sq. km. Although the salt is probably part of the Muddy Creek Formation, its exact relationship to the Virgin Valley deposit has not been fully established.

The presence of a thick sequence of rock salt at moderate depth shows some promise with regard to the storage of radioactive waste, but much additional data are needed on the geology and hydrology to evaluate this occurrence more fully. Data are needed particularly on the structure, extent, and lithology of the salt body. Also to be evaluated are the potential for developing glauberite or other mineral resources, the tectonic activity of the area, and the extent of the salt body within the Lake Mead Recreation Area.

Sevier Valley (Utah)

Thick deposits of salt underlie a fairly large portion of central Utah (fig. 62) and are exposed at the surface in three small areas of the Sevier River Valley along the Sevier-Sanpete County line. Early workers placed the outcropping salt in the Jurassic Arapien Formation, whereas later subsurface studies showed correlation of the Arapien with typical Carmel strata farther east: the salts are now considered part of the Carmel-Arapien shales and evaporites (Moulton, 1975). Outcrops of salt are along the crest of an anticline that probably resulted from diapiric upward movement of evaporites from the deep subsurface. Information on surface geology relating to the Sevier Valley salt deposits is contained in reports by Spieker (1949), Gilliland (1951), Hardy (1952), Pierce and Rich (1962), and Pratt and others (1966); data on salt in the subsurface were presented by Moulton (1975), Loucks (1975), and Bertram (1975).

Outcrops of the Arapien Formation at Redmond Hills and nearby areas consist of red and gray shales interbedded with sandstone, limestone, salt, and lenses of gypsum (Pratt and others, 1966). A maximum of 60 m of salt is exposed by quarry operations in the area, but operators estimate the total thickness to be about 300 m. Most of the salt is brick red in color, owing to finely disseminated red clay, but is still remarkably pure (95 to 97 percent halite). Younger rocks present are Tertiary through Holocene limestones, sandstones, siltstones, pyroclastics, gravels, and valley fill.

At Redmond Hills the salt is brought to the surface along an anticline with steep-dipping flanks of 20° to 40°. The anticlinal folding, even present in Holocene gravels, suggests continued upward flowage of the plastic salt beds. Salt is fairly to poorly bedded at Redmond Hills and locally appears brecciated and recrystallized (Pratt and others, 1966). The salt is cut by large vertical joints and by smaller horizontal stress-release joints.

Recent drilling by Phillips Petroleum Co. showed that the Carmel-Arapien salts occur in a large north-northeast-trending belt that underlies much of Sanpete and Sevier Counties (Moulton, 1975; Bertram, 1975). A rift zone, about 25 km wide and at least 100 km long, was downwarped during Middle Jurassic time and was filled with evaporites, carbonates, and clastic sediments. The Carmel-Arapien salt unit appears to be more than 2,500 m thick locally in the rift zone, but these thick salt-shale sequences may be due in part to diapiric flow (Moulton, 1975). This salt deposit may be related to other Jurassic salts farther north in the Idaho-Utah-Wyoming border area (Loucks, 1975).

The seven wells drilled into the salt reached it at depths ranging from 1,800 to 3,600 m below the surface. In most wells the salt was thin (less than 20 m) or only the top 30 m was drilled; however, one well in north-central Sanpete County penetrated about 600 m of salt at a depth of 2,700 m (Moulton, 1975; Bertram, 1975).

The Sevier Valley salts appear to underlie a large area, at depths generally greater than 1,800 m. They crop out and are at shallow depth along a complex anticlinal structure, the core of which probably contains a considerable thickness of salt that has undergone plastic flow. Although little is known at present about the subsurface geology and the geohydrology of the area, it is possible that subsequent study may establish the presence of a salt body with potentially desirable characteristics.

Eagle Valley (Colorado)

The Eagle Valley Evaporite is a thick sequence of clastic and evaporite rocks on the western side of the Rocky Mountains in northwestern Colorado (fig. 63). Halite is present within strata of the Eagle River Valley (Eagle County) and the Cattle Creek Valley (Garfield County) at localities that are, respectively, 40 km east and 10 km south of Glenwood Springs. Salt in the subsurface was discovered near the town of Eagle in 1949, but since that time only limited data have been collected on this halite occurrence. Reports dealing with the halite and other evaporites include those by Katich (1958), Mallory (1966, 1971), and Peterson and Hite (1969).

Although the Eagle Valley Evaporite consists principally of gypsum and anhydrite interbedded with gray shale, siltstone, and sandstone, it also includes an appreciable quantity of halite locally and traces of potash salts (Mallory, 1971). The evaporite-bearing sequence interfingers with red and maroon clastic sediments of the Middle Pennsylvanian (late Atokan and Desmoinesian) Minturn Formation. Evaporites were deposited in a landlocked marine trough between the Uncompahgre and Front Range uplifts.

Based on the few boreholes that have penetrated salt, and on regional geologic studies, Mallory (1971) showed that an area about 500 sq. km in Eagle Valley and about 70 sq. km near Cattle Creek is underlain by halite. Near the town of Eagle, halite occurs 450 m below the surface and is interbedded with anhydrite, shale, and siltstone to a maximum depth of 1,600 m. Halite units appear to be 10 to 60 m thick, based upon an examination of one gamma-ray log, but these thicknesses may be abnormal owing to salt flowage. In two other boreholes, halite is present about 425 m below the surface, while two beds containing potash, 1.8 and 2.1 m thick, were reported at depths between 1,100 and 1,220 m (Mallory, 1971). In a borehole at Cattle Creek, halite is the principal rock from 650 m below the surface to a total depth of 930 m.

Since its deposition, the Eagle Valley Evaporite has been subjected to the following stresses: (1) load metamorphism, (2) Laramide orogenic movement, (3) growth of diapiric anticlines, and (4) local contortion from flowage and hydration of anhydrite (Mallory, 1971). Outcropping strata of the evaporite unit are deformed in most areas, and Mallory (1971) felt that the evaporite mass may still be rising in the cores of several anticlines.

Even though thick layers of rock salt are apparently present at moderate depth in the Eagle River and Cattle Creek Valleys, much additional data are needed on the structure, thickness, extent, and lithology of the salt in order to evaluate this occurrence. Data also are needed on the potash resources and hydrology, as well as on the significance of the recreational sites at and near Glenwood Springs and Vail.

Piceance Basin (Colorado)

Salt is interlaminated with nahcolite ($NaHCO_3$) in the rich oil-shale deposits of the Piceance basin in northwestern Colorado (fig. 63). Two halite-bearing zones are known here in the lacustrine Parachute Creek Member of the Early Tertiary (Eocene) Green River Formation. Salt underlies an area estimated to cover about 125 sq. km in Rio Blanco County. The principal report on salt within the Piceance basin is by Dyni and others (1970), although later reports on associated saline deposits were done by Beard and others (1974) and Dyni (1974).

The upper halite-bearing zone is about 60 m thick; the top occurs about 550 m below the surface (Dyni and others, 1970). A thinner, lower zone, about 30 m in thickness, is separated from this upper zone by about 45 m of nahcolitic oil shale that locally also contains a thin salt unit. Above the upper halite-bearing zone is a "leached" zone of rocks consisting of about 100 m of broken and brecciated oil shales from which preexisting soluble salts have been dissolved. Open solution cavities are common in the leached zone, whose base is a dissolution surface that cuts irregularly across rock-stratigraphic units. The leached zone contains water that is probably still removing water-soluble minerals along this dissolution surface.

Based on core information, the upper and lower halite-bearing zones consist of thin-bedded to thinly laminated halite and nahcolite that form rock units 2 to 20 m thick (Dyni and others, 1970). These units are interbedded with nahcolite-rich oil-shale layers that vary from 3 to 7 m in thickness. Alternating layers of halite and nahcolite form couplets that commonly are 2 to 15 cm thick. The ratio of halite to nahcolite in these couplets is about 3:2.

Mineral resources within the Piceance basin that might be commercially developed in the future include oil shale, nahcolite, and dawsonite ($NaAl(OH)_2CO_3$), all of which are closely associated with the halite deposits previously described. In addition, natural gas is being produced from pre-Green River reservoirs in a number of fields scattered throughout the basin.

Salt deposits of the Piceance basin are at moderate depth, but individual layers are thin and dissolution of the upper salt is probably still taking place. Although additional studies are needed to evaluate the potential for development of oil shale, nahcolite, dawsonite, and natural gas in the area, the basin does not appear to contain enough characteristics favorable for the storage of radioactive waste.

Green River Basin (Wyoming)

Salt (halite) occurs in small quantities with the trona deposits within the Green River basin of southwestern Wyoming (fig. 63). Known occurrences underlie about 300 sq. km in Sweetwater County and are restricted to the lower Wilkins Peak Member of the Green River Formation. The latter stratigraphic unit is a lacustrine deposit of Early Tertiary (Eocene) age. Data on this salt are found mainly in reports by Deardorff (1963), Culbertson (1966, 1971), and Deardorff and Mannion (1971).

The lower Wilkins Peak Member embraces 16 extensive trona beds, 13 of which contain salt, at depths ranging from 200 to 750 m. There are no known extensive beds of halite alone (Deardorff, 1963). The salt is usually mixed with the trona, although thin units of almost pure halite occur locally as part of a thicker evaporite bed. These pure salt units are usually much less than 1 m thick.

Salt layers of the Green River basin occur at moderate depths, but they are quite thin. The trona deposits interbedded with these salts represent the world's largest known reserve of natural soda ash, and several companies are now producing trona from underground mines. The Green River Formation also contains oil-shale resources that might be exploited at some time in the future. Thus the salts of this basin do not warrant further consideration at this time.

Idaho-Utah-Wyoming Border

Salt-bearing strata of Jurassic age are present at shallow depth in southeastern Idaho and have been penetrated by deep wells in north-central Utah and southwestern Wyoming (fig. 63). Salt occurs in a sequence of interbedded red shale, anhydrite, and limestone in the lower part of the Preuss Formation (Pierce and Rich, 1962). The structure of the salt beds is complicated, because the region is one of intense folding and faulting in the overthrust belt of the Middle Rocky Mountains just west of the Green River basin. Although brine and bedded salt have been utilized here for more than 70 years, there has been little study of the salts. The principal recent reports are by Peterson (1955, 1957), Pierce and Rich (1962), and Lefond (1969).

Rock salt was discovered in this area in 1902 while deepening a brine spring on Crow Creek in southeastern Idaho. The salt, which is impure and contains a high percentage of shale fragments, is as shallow as 2 m below the surface, and in one of the open pits 6 m of salt was penetrated without reaching the bottom (Breger, 1910). A well drilled 15 km farther north was reported by Mansfield (1927) to have penetrated about 140 m of salt-bearing strata containing 6 salt beds 2 to 9 m thick; the depth to the top of the salt was about 37 m.

Two deep wells confirmed the presence of salt in north-central Utah. The Ohio Oil Co. No. 1 Wilde (sec. 9, T. 2 N., R. 5 E.) penetrated halite from 2,460 m to its total depth of 2,590 m, and the Utah Southern Oil Co. No. 1 Hatch (sec. 28, T. 6 N., R. 8 E.) drilled 210 m of interbedded halite, anhydrite, and sandstone at a depth of 1,800 m (Peterson, 1955). Geophysical logs of both wells indicate that the salt is impure.

Data on the salt beds are meager, and little is known about the areal extent of salts in the Preuss Formation. Pierce and Rich (1962) felt that the salt was probably deposited in a southeast-trending basin or a series of basins that may have extended about 160 km through the three states. The width of the salt area may be as much as 100 km, but the region is intensely folded and faulted and the salt beds probably are not continuous. The complexity of the geology in the overthrust belt is shown in the recent work by Royse and others (1975). The salt deposits here may be related to, though not necessarily connected with, the Sevier Valley salts in the Jurassic Carmel-Arapien sequence of central Utah (Loucks, 1975).

In summary, the Idaho-Utah-Wyoming border area is structurally complex, and the salt deposits are somewhat impure and discontinuous. The salt is quite deep (more than 1,800 m) in the only wells that have penetrated a moderately thick salt sequence. Additional data are needed to evaluate this deposit more fully, particularly in the northern area, where the salt may lie at moderate depth.

Northern Denver Basin (Nebraska-Colorado-Wyoming)

A fairly thick sequence of rock salt is present in the northern part of the Denver basin, in parts of western Nebraska, northeastern Colorado, and southeastern Wyoming (fig. 63). Parts of the area also have been referred to as the Lusk embayment (Bates, 1955) and the Alliance basin (MacLachlan and Bieber, 1963; Maughan, 1966; Rascoe and Baars, 1972). These reports, and one by Lane (1973), are the principal sources of information on the salt deposits of this area. The total thickness of salt-bearing strata is as much as 200 m, but the top of the salt appears to be more than 900 m below the surface in all but the northeastern part of the basin.

Salt occurs in several formations of Permian age, including (in ascending order) the Minnelusa, Owl Canyon, Opeche, and lower part of the Goose Egg Formations (Maughan, 1966). Halite in the Minnelusa and Owl Canyon seems to be localized only in parts of the area, although it may have originally been deposited more widely and subsequently leached. Collapsed breccias in outcrops of these rocks in the Black Hills, the Hartville uplift, and the northern part of the Laramie Range probably resulted in part from dissolution of this salt.

The Opeche Shale consists mainly of red beds and evaporites and locally includes significant beds of halite in western Nebraska and southeastern Wyoming (Maughan, 1966; Rascoe and Baars, 1972). As much as 75 m of salt-bearing strata was deposited in parts of the area. Individual beds of rock salt appear to be 5 to 20 m thick, and they are interbedded with minor amounts of anhydrite and fine-grained clastics. The salt is less pure toward the margin of the halite area where it interfingers with additional layers of anhydrite and detrital sediments.

Salt is also present in the overlying Goose Egg (Spearfish) Formation in much the same area as that of the Opeche halite (Maughan, 1966). As much as 60 m of relatively pure halite accumulated in parts of the area, with individual beds of rock salt reaching a thickness of at least 15 m. Interbedded with the salt are layers of anhydrite, dolomite, and fine-grained clastics. Salts in the Goose Egg and Opeche Formations are separated by 15 to 30 m of anhydrite, limestone, dolomite, and shale, chiefly in the Minnekahta Limestone.

The area of maximum thickness of salt-bearing strata appears to be in Box Butte and southern Sioux Counties, Nebraska (MacLachlan and Bieber, 1963), where nearly 200 m of interbedded evaporites and clastics are about 1,200 to 1,700 m below the surface. Permian strata dip gently to the west and southwest, away from the Chadron arch, and thus the salt units are generally deeper in that direction. East of this area, on the west flank of the Chadron arch, the salts are thinner and at shallower depth. In eastern Box Butte and Dawes Counties, northwestern Nebraska, the salt units thin somewhat abruptly, but locally as much as 60 m of salt-bearing strata may be only 900 m below the surface.

Oil and some natural gas are produced from a large number of fields in the southwestern part of the Nebraska Panhandle and nearby parts of Colorado and Wyoming. These fields produce mainly from rocks of Cretaceous age, and the area of production is south of the principal salt deposits in Sioux, Box Butte, and Dawes Counties.

Data currently available indicate that there may be areas in the Northern Denver basin where thick Permian salts are present at moderate depth and thus warrant further study. Additional studies are needed to fully evaluate the thickness and depth of the salts and the geohydrology, with special attention being given to Box Butte and Dawes Counties, northwestern Nebraska, and to other nearby areas.

Powder River Basin (Wyoming)

Salt occurs in the Permian Goose Egg Formation deep below the surface in the Powder River basin, a large structural and sedimentary basin in northeastern Wyoming and southeastern Montana (fig. 63). This asymmetrical basin is bounded by the Black

Hills on the east, the Big Horn Mountains on the west, the Laramie and Hartville uplifts on the south, and a gentle unnamed arch on the north (Curtis and others, 1958). Strata dip gently southwestward, at an angle of 1°, across most of the basin to the structural and depositional axis, where more than 5,000 m of sediments overlies Precambrian basement.

The Goose Egg Formation, which is equivalent in part to the Spearfish Formation to the east and northeast, contains salt only at the top in the Ervay Member (Lane, 1973). Salt is limited to the Wyoming portion of the basin, where it underlies most of Campbell County and parts of Sheridan, Johnson, Converse, Niobrara, and Weston Counties. The total thickness of the salt-bearing unit is typically 30 to 60 m, and individual salt beds appear to be as thick as 10 m. The depth below land surface to the top of the salts in the Goose Egg Formation is typically 2,000 to 4,500 m, and generally this is considered too deep for underground mining at present.

Williston Basin (North Dakota–South Dakota–Montana)

Several units of rock salt are present in the Williston basin, a large sedimentary and structural basin that underlies most of North Dakota, the eastern part of Montana, northwestern South Dakota, and part of southern Canada (fig. 63). Strata dip gently at an angle less than 1° toward the depocenter of the basin, where about 5,000 m of sedimentary rock of Cambrian through Tertiary age is preserved (Carlson and Anderson, 1965). Major structural features in the basin are the Nesson anticline, a north-trending structure in northwestern North Dakota, and the Cedar Creek anticline, a structure that extends northwestward into Montana from the common corner of North Dakota, South Dakota, and Montana. Oil and gas are produced along both of these structures and also from a few other fields scattered through the basin.

Five moderately thick units of bedded rock salt (halite) occur in strata ranging in age from Devonian through Jurassic. Stratigraphic units represented are the Prairie Formation (Devonian), Madison Group (Mississippian), Opeche Formation (Permian), Pine Salt (Permian-Triassic), and Dunham Salt (Jurassic) (fig. 67). The aggregate thickness of salt in each unit is 30 m to nearly 150 m. Most salts in the Williston basin are at least 1,500 m below the surface, with the exception of the Pine Salt, which is as shallow as 900 m along the south edge of the basin near the common corner of South Dakota, Montana, and Wyoming (fig. 68). Salt deposits of the Williston basin were studied by Zieglar (1956), Anderson and Hansen (1957), Sandberg (1962, 1973), Pierce and Rich (1962), Maughan (1966), and Lefond (1969).

The oldest and generally deepest salt is the Prairie Formation of Devonian age. That part of the formation present in the United States is only the southern end of a large evaporite basin that extended across much of the Canadian provinces of Saskatchewan, Alberta, and Manitoba. Salt occurs in the upper part of the formation in parts of North Dakota and Montana, where it reaches a maximum thickness of nearly 150 m (fig. 68). The salt unit consists chiefly of thick, massive beds of halite, but it does contain several interbeds of potash (sylvite and sylvinite) with an aggregate thickness of about 12 m (Carlson and Anderson, 1966). The depth to the Prairie Formation salts is 1,500 to 3,600 m in all parts of the basin.

The next youngest salts of the Williston basin occur in the Madison Group of Mississippian age. Individual beds of massive halite are typically 10 to 50 m thick and extend over large parts of the basin. The maximum aggregate thickness of all salt beds in the Madison is nearly 120 m, which is reached in the deepest part of the basin along the North

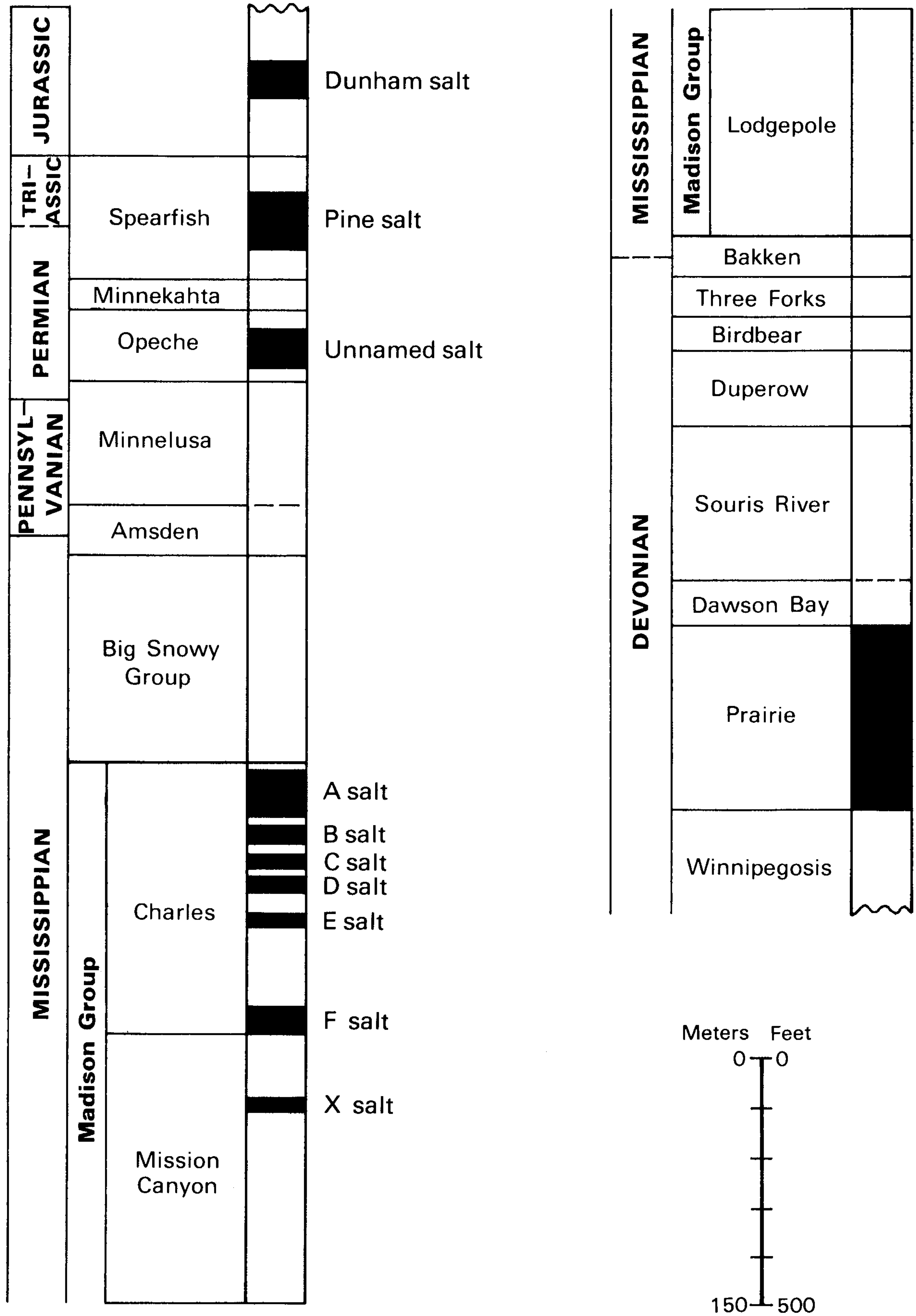


Figure 67. Generalized columnar section of salt-bearing strata in Williston basin (modified from Pierce and Rich, 1962).

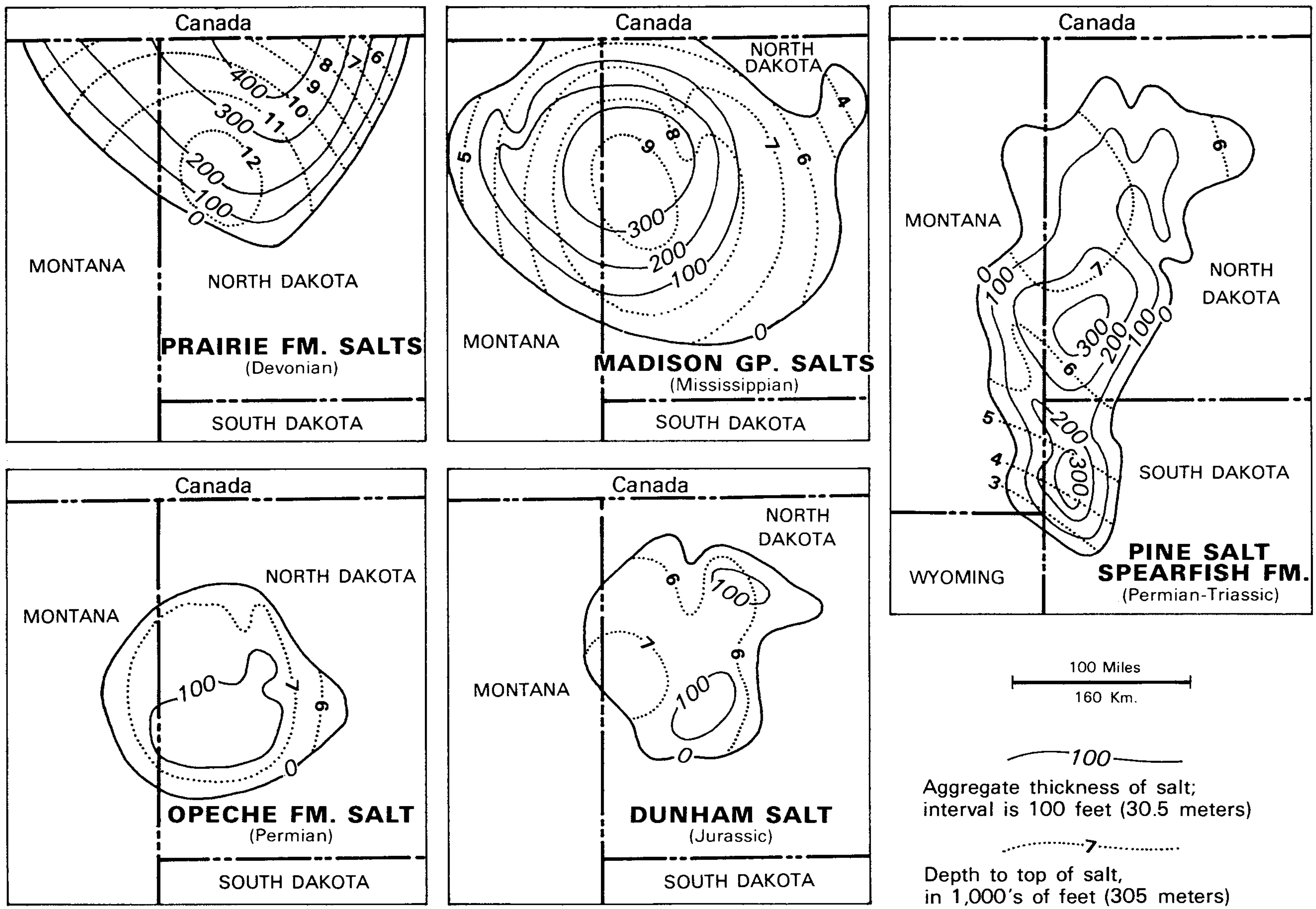


Figure 68. Maps showing aggregate thickness in feet and depth below land surface to top of salt beds in Williston basin. Based on data from Zieglar (1956), Anderson and Hansen (1957), Sandberg (1962), and Lefond (1969).

Dakota–Montana border (fig. 68). The top of the salt is 1,500 to 2,700 m below land surface in most parts of the basin. Only in the east is the salt as shallow as 1,000 to 1,500 m, but the one salt bed present in this area is only 6 to 12 m thick. The youngest salt is now being solution mined from a depth of 2,400 m at Williston, North Dakota, and is the only salt bed being developed at present in the basin.

An unnamed salt bed occurs in the Permian Opeche Formation in the central part of the Williston basin. The aggregate thickness of this salt is more than 30 m in a moderately large area, and locally it is as thick as 45 m (fig. 68). The depth to the top of the salt is about 1,800 to 2,200 m in all parts of the basin. The salt apparently is impure and lenticular and grades abruptly into shale and anhydrite.

The Pine Salt is a moderately thick unit within the Spearfish Formation of Late Permian–Early Triassic age (Zieglar, 1956). This unit appears to be a massive bed of fairly pure halite in most areas and is more than 90 m thick in two separate depocenters located in North Dakota and South Dakota (fig. 68). The top of the salt is about 1,600 to 2,200 m below the surface in North Dakota and adjacent Montana, whereas it is slightly less than 900 m to as much as 1,800 m deep in the southern depocenter of South Dakota and adjacent areas. The southern depocenter coincides with the northwest-trending Ekalaka syncline, which is bounded on the north by the Cedar Creek anticline and on the south by the Black Hills uplift. Although data on the south flank of the Ekalaka syncline have not been fully evaluated, the salt apparently thins fairly abruptly to the southwest but may still be moderately thick locally where it is about 900 m below the surface. Additional studies are needed to establish the thickness and depth of the Pine Salt in this area, which includes part of Butte County, South Dakota, southeastern Carter County, Montana, and northeastern Crook County, Wyoming.

The youngest salt in the Williston basin is the Dunham Salt of Jurassic age (Zieglar, 1956). It reaches a maximum thickness of about 30 m in two separate areas in western North Dakota (fig. 68). The depth to the top of the Dunham salt ranges from about 1,500 to 2,100 m in all parts of the basin.

In summary, several of the salt units in the Williston basin are thick enough to be considered for waste storage, but some of them may be too deep for underground mining at this time. These deep salts may be suitable later for second-generation (solution-cavern) storage of low-level wastes. The Pine Salt may be sufficiently thick locally and at a suitable depth, especially in the southern part of the basin, but additional studies are needed to evaluate this salt and the local geohydrology.

Saltville Area (Virginia)

Rock salt is present as a tectonic breccia in the tightly folded and faulted Valley and Ridge province of western Virginia (fig. 1). This occurrence is within the Maccrady Formation of Mississippian age and appears to be restricted to a small area around Saltville in Smyth and Washington Counties. Although brine wells have been operated here since the early 1800's, the salt beds have been little studied at depth. All salt mining has been through brine wells, but two underground gypsum mines currently operate in the district. The main data on the Saltville area are in the report by Cooper (1966).

The structure of the salt beds is complicated. Salt is preserved in a major fold, the Greendale syncline, which has been overturned on the south limb and has been overridden by Cambrian rocks forming the sole of the Saltville thrust (Cooper, 1966). The dip of the Maccrady beds is typically 25° to 70°, and the strata are highly contorted locally.

In some of the deeper brine wells of the area, the Maccrady Formation is 450 to 510 m thick and contains considerable amounts of salt, gypsum, anhydrite, dolomite, and limestone interbedded with red and green plastic shale (Cooper, 1966). Some well records show an aggregate of 240 m of salt spread through 12 to 20 different zones. The salt ranges from several tens of meters to as much as 1,000 m below the surface.

Cores taken from the overturned (upper) limb of the Greendale syncline in 1961 provide information on the character of the salt. The salt occurs as zones of tectonic breccia wherein fragments of shale, anhydrite, limestone, and dolomite are suspended in a matrix of salt (Cooper, 1966). In most breccia zones, salt makes up 60 to 75 percent of the rock. Cooper (1966) believed that an original primary sequence of salt interbedded with the other rock types was sheared and broken up during overturning and that rock fragments were thus engulfed in the salt matrix. He believes that some of the salt in the upright (lower) limb is brecciated but also feels that some of it may be nonbrecciated.

A recent wildcat well drilled by the Westinghouse Co. penetrated a considerable thickness of salt below the sole of the Saltville thrust, but complete data from this well are obscured by difficulties encountered during drilling (Bartlett, 1977, personal communication).

The Saltville area is structurally complex, and the salt deposits are generally brecciated, impure, and heterogeneous. A number of boreholes have been drilled in the area for brine production, and several mines have been opened for development of gypsum resources. Subsidence and water pollution resulting from brine-well operations forced the American Cyanamid Co. to cease operations. Thus the regional character of this deposit indicates that it does not deserve further consideration at this time.

Southern Florida

Several petroleum boreholes have penetrated thin beds of Cretaceous rock salt at great depth in the southwestern part of the Florida Peninsula (fig. 1). Correlation of salt units in the area is difficult, owing to the wide spacing of tests, and it is not certain whether there is one extensive salt basin or several smaller isolated basins. Halbouty (1967) referred to these occurrences as the Sunniland salt basin, in part because the first well to penetrate the salt was drilled near the Sunniland oil field. The limited data from scattered wells indicate that the salt deposits extend north at least to Charlotte Harbor and south to Big Pine Key.

The salt is associated with anhydrite, limestone, dolomite, and minor amounts of dark shale in the Lower Massive Anhydrite of Early Cretaceous age (Pierce and Rich, 1962). The shallowest salt penetrated is more than 3,300 m below the surface, whereas several wells have encountered salt at depths greater than 3,600 m. The total thickness of the salt does not exceed 10 m, and most beds are 3 m thick or less.

Even though the data from this area are limited, the thinness and great depth of these salt beds preclude their further consideration at this time.

SUMMARY AND CONCLUSIONS

A repository for radioactive waste must isolate radionuclides from the biosphere for long periods of geologic time, during which time the radionuclides would decay to the point where they no longer represent a hazard to man and his ecosystem. Burial of waste in a solidified form in subsurface geologic formations has been considered the most effective and most practical means of isolation, and the characteristics of thick deposits of rock salt make these deposits a desirable medium for such geologic isolation.

This report brings together an extensive body of data on the distribution and geology of rock-salt deposits in the United States and discusses for each salt deposit the regional geologic characteristics that relate to its general suitability for the possible storage or disposal of radioactive waste. These regional geologic characteristics include the thickness, depth, lateral continuity, homogeneity, and dissolution of salt beds, as well as the geologic structure, hydrology, and seismic activity of the region. Other characteristics include the nature of rock units adjacent to the salt, the potential for present or future development of mineral resources, and the location of boreholes and other man-made excavations that penetrate the salt.

A total of 19 sedimentary basins or regions containing rock-salt deposits are known to underlie parts of 25 of the 50 states. These salt deposits consist almost entirely of the mineral halite, although some are closely associated with and interbedded with other sedimentary rocks. Bedded rock salt is the major form of salt masses in most of these basins, although diapiric salt domes and salt anticlines are dominant in several areas.

In the northeast, the Michigan and Appalachian basins contain thick salts at moderate depths that may be suitable for radioactive-waste storage locally in parts of Michigan, Ohio, and New York. The Silurian Salina salts are nearly flat lying and have not been dissolved or structurally deformed and fractured except in parts of New York and Pennsylvania, and both basins are characterized by low seismic activity and low seismic risk. The maximum aggregate thickness of the Salina salts is 600 m in the center of the Michigan basin and more than 150 m in deep parts of the Appalachian basin: these salts thin toward the shallow margins of the basins, but major salt units are still as thick as 60 m at depths less than 900 m in large parts of both basins. Both basins contain substantial areas that have a low mineral potential and that are free of boreholes or mines that penetrate the salt. Many of the regional characteristics favorable for waste storage are found in the northeastern part of Michigan's Southern Peninsula as well as in parts of northeastern Ohio, southwestern New York, and south-central New York. The Devonian-age Detroit River salts also are thick and at moderate depth in the north-central part of the Michigan basin.

The Gulf Coast region contains some 263 known or strongly inferred salt domes within the onshore portions of 5 separate salt-dome basins, the Northeast Texas, North Louisiana, and Mississippi interior basins and the Texas-Louisiana and South Texas coastal basins. In a total of 113 of these domes, the top of the salt is more than 1,000 m below the surface and thus is beyond the optimum depth for mechanical mining. Of the remaining 150 domes, 95 have undergone industrial development; such development includes (1) production of petroleum from above or along the flanks of certain domes, (2) production of rock salt or brines from the central salt cores, (3) storage of either LPG or crude oil in solution caverns formed within the salt masses, and (4) production of Frasch sulfur from overlying cap-rock units. Although all the domes now utilized by industry are not to be considered unacceptable in a final sense, especially where the activities have not affected the salt mass directly, their current status of development places them in a lower priority with regard to ongoing investigation.

The remaining 55 domes of shallow to moderate depth that are not utilized by industry are nearly all located in the 3 interior basins, where the domes fortunately are not undergoing tectonic (diapiric) uplift and appear to have undergone no upward movement for nearly 20 million years. Most of these 55 domes have a cap rock, which is believed by most investigators to have resulted from past dissolution of the upper part of the rising salt masses. The presence of surface salines and the apparent occurrence of saline plumes in various fresh-water aquifers at several interior-basin domes have also been investigated with regard to their hydrologic implications. However, much additional hydrologic, geophysical, and drilling information needs to be acquired on most of these domes before even their preliminary acceptability can be established. Owing to their generally shallower depths, apparent tectonic stability, and more abundant existing data, domes within the Northeast Texas and North Louisiana basins appear to offer more potential for storage of high-level radioactive waste. Although many of the domes in the Mississippi basin are somewhat deeper and are severely lacking in basic information, they also exhibit significant promise. In none of these basins is it possible at this time to identify one or more domes that are clearly more acceptable than the others.

The Permian basin contains eight principal salt units in various parts of Texas, New Mexico, Oklahoma, Kansas, and Colorado. The salts, all of which are Permian in age, are not structurally deformed or fractured, and there are large areas where thick salts at moderate depth have not been dissolved. The region is characterized by a low seismic risk and few recorded earthquakes, and it has been tectonically stable since deposition of the salt beds. Salt units consist mainly of rock salt, but typically they are interbedded with shale, anhydrite, and/or dolomite. Most salt units are 100 to 200 m thick and are at depths of 300 to 900 m in large areas of each state. Petroleum production, mineral potential, and the number of existing boreholes and mines penetrating salt beds are low in several of the structural basins and in some broad shelf areas outside of these basins. Among the large areas where regional characteristics important for waste storage are generally more favorable are the Palo Duro basin of Texas, the Dalhart basin of the Texas and Oklahoma Panhandles, and broad shelf areas in parts of southeastern New Mexico, southeastern Colorado, and western Kansas.

Salt anticlines in the northeastern part of the Paradox basin of Utah and Colorado may locally be suitable for underground storage of radioactive waste. Pennsylvanian-age rock salt has flowed diapirically to form the thick central cores of the anticlines, and only in the anticlines is the salt at relatively shallow depths. Numerous salt beds, each typically 20 to 80 m thick, are interbedded with black shale, dolomite, anhydrite, and (in some evaporite cycles) potash. Few boreholes or mines have penetrated the cores of the anticlines, and the potential for future discovery of petroleum and other minerals (with the exception of potash) is away from the core areas. The basin is an area of low seismic risk, with no earthquakes of MM V or greater having been recorded in the salt region. Two structures in Utah, Salt Valley anticline and Shafer dome, contain thick salts that do not appear to be too complex and that are 200 to 500 m below the surface: these areas have many characteristics that may locally be favorable for waste storage, and they warrant further detailed investigation. In addition, some of the other salt anticlines may locally be found suitable as a result of subsequent study.

The Supai salt basin of east-central Arizona contains a single salt-bearing sequence 100 to 300 m thick in the Supai Formation of Permian age. The salt is interbedded with sandstone, shale, limestone, anhydrite, and potash (in the north), and the top of the salt is typically 300 to 750 m below the surface. Salt beds dip gently to the north and are not structurally deformed, except along and south of the Holbrook anticline, where the salt has been partly or completely removed by dissolution. Recorded seismic activity has not been significant, but the basin is considered part of a moderate-damage risk area (zone 2). Boreholes or other man-made excavations into the salt are sparse, except in the northern and northeastern parts of the basin where helium is being produced commercially and where potash has been prospected. Petroleum potential for the basin appears to be low, but special geohydrologic studies are needed on the Coconino-Kaibab-upper Supai aquifer system, which is 30 to 60 m above the salts. In summary, many of the regional characteristics favorable for waste storage appear to be present in parts of the Supai salt basin, chiefly in the central area, which is far removed from the Holbrook anticline and the helium and potash deposits.

The remaining salt deposits in the United States are generally smaller, or at least the areas underlain by thick salts at optimum depth are smaller; but in some of these areas many of the regional geologic characteristics are favorable, and subsequent study may show they are locally suitable for radioactive-waste storage. Thick salts are present within the optimum depth range of 300 to 900 m in the following 7 basins or provinces of the western United States: Luke (Arizona), Red Lake (Arizona), Virgin Valley (Nevada and Arizona), Eagle Valley (Colorado), southern part of Williston (South Dakota-Wyoming-Montana area), northern part of Northern Denver (northwestern Nebraska), and the salt-anticline area of Sevier Valley (Utah). Salts of the Luke, Red Lake, Williston, and Northern Denver basins are nearly flat lying and have not been deformed structurally, whereas the Virgin Valley, Eagle Valley, and Sevier Valley salts all have been deformed plastically and have formed thick diapiric masses. In all seven areas, the number of boreholes or mines penetrating the salts is relatively low: this helps minimize the potential for migration of ground water to salts through man-made openings, but the evaluation of these areas for potential waste repositories is more difficult without such additional data.

Some of the other salt deposits are thick, but they are at depths now considered greater than the optimum depth for underground mechanical mining (greater than 900 m deep). Five basins or provinces included in this category are the Powder River basin (Wyoming), the Utah portion of the Idaho-Utah-Wyoming deposit, and most parts of the Sevier Valley (Utah), Williston (North Dakota-Montana-South Dakota), and Northern Denver (Nebraska-Colorado-Wyoming) basins. The tops of these salts are typically more than 1,800 m deep, but there are areas in the 900 to 1,800 m range in parts of the Sevier Valley, Williston, and Northern Denver basins. Salts in one or more of these five provinces may be suitable locally for waste disposal, if other geologic characteristics are especially favorable and if problems of mechanical mining at such depths can be overcome, or they may be suitable for second-generation (solution-cavern) storage of low-level wastes.

The few remaining salt deposits do not appear to have enough favorable characteristics to warrant further serious consideration at this time for storage of high-level radioactive waste. The shallow depth and structural complexity of salts in the Saltville area (Virginia) and the northern part of the Idaho-Utah-Wyoming deposit adversely affect their potential for such use, and the Saltville area is further jeopardized by the numerous boreholes, brine wells, and mines in the evaporites. The use of salts in the Piceance (Colorado) and Green River (Wyoming) basins is improbable, because individual halite layers are less than 1 m thick and they are interbedded and interlaminated with oil shale, trona, nahcolite, and/or dawsonite resources that are being mined or may be mined in the future. The salt deposits of southern Florida are so thin (10 m or less) and so deep (more than 3,300 m) that they do not deserve further consideration at this time.

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