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SUBSURFACE GEOLOGY AND POROSITY DISTRIBUTION, MADISON LIMESTONE AND UNDERLYING FORMATIONS, POWDER RIVER BASIN, NORTHEASTERN WYOMING AND SOUTHEASTERN MONTANA, AND ADJACENT AREAS

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Abstract

To evaluate the Madison Limestone and associated rocks as potential sources for water supplies in the Powder River Basin and adjacent areas, an understanding of the geologic framework of these units, their lithologic facies patterns, the distribution of porosity zones, and the relation between porosity development and stratigraphic facies is necessary.

Regionally the Madison is mainly a fossiliferous limestone. However, in broad areas of the eastern Rocky Mountains and western Great Plains, dolomite is a dominant constituent and in places the Madison is almost entirely dolomite. Within these areas maximum porosity development is found and it seems to be related to the coarser crystalline dolomite facies. The porosity development is associated with tabular and fairly continuous crystalline dolomite beds separated by non-porous limestones.

The maximum porosity development in the Bighorn Dolomite, as in the Madison, is directly associated with the occurrence of a more coarsely crystalline sucrosic dolomite facies. Well data indicate, however, that where the Bighorn is present in the deeper parts of the Powder River Basin, it may be dominated by a finer crystalline dolomite facies of low porosity.

The "Winnipeg Sandstone" is a clean, generally well-sorted, medium-grained sandstone. It shows good porosity development in parts of the northern Powder River Basin and northwestern South Dakota. Because the sandstone is silica-cemented and quartzitic in areas of deep burial, good porosity is expected only where it is no deeper than a few thousand feet.

The Flathead Sandstone is a predominantly quartzose, slightly feldspathic sandstone, commonly cemented with iron oxide. Like the "Winnipeg Sandstone," it too is silica-cemented and quartzitic in many places so that its porosity is poor in areas of deep burial.

Illustrations in this report show the thickness, percent dolomite, and porosity-feet for the Bighorn Dolomite and the Madison Limestone and its subdivisions. The porosity-feet for the "Winnipeg" and Flathead Sandstones and four regional geologic sections are also shown.

Introduction

This study was carried on as part of the U.S. Geological Survey Madison aquifer project to evaluate the Madison Limestone and associated rocks as potential sources for water supplies to help meet future water needs in a 188,000-mi^2 region that includes the coal-rich area of the Northern Great Plains. The purpose of this phase of the work is to establish the subsurface geologic framework of the Madison and deeper stratigraphic units, to define their lithologic facies patterns, to delineate and map the distribution of porosity zones, and to determine the relationships between stratigraphic facies and porosity development in the Powder River Basin, northeastern Wyoming and southeastern Montana, and adjacent areas. Beyond that, the ultimate aim is to develop a system of predictable models for the geologic framework and porosity zones as an aid to exploration and development of ground-water resources in the region. Primary emphasis of the study is on the Madison Limestone, but the underlying lower Paleozoic units were studied also. As far as possible at this early stage of the project, preliminary maps have been constructed for the more important potentially water-yielding geologic units. The area covered in this report is about 75,000 mi^2 (fig. 1).

The Madison as a geologic unit has been extensively studied since the time of the early government surveys, although most of the detailed stratigraphic work has been done since World War II. Much of the later stratigraphic and paleontologic work on the Madison is that of W. J. Sando. Reference is made to his publications, and those by Andrichuk (1955), Mamet (1971), Craig (1972), and others listed in the Selected references, for a thorough background geology of the Mississippian System. A recent paper by Rose (1976) gives an excellent regional summary of the Mississippian in the western United States. In addition to the numerous published reports, the Madison has received extensive study and attention by many petroleum geologists throughout the Rocky Mountain area.

Almost all data used in the identification and correlation of stratigraphic marker horizons, strata-thickness compilations, and porosity calculations were obtained from gamma ray-neutron, sonic, and electric logs of oil wells located mainly around the flanks of the Powder River and Williston Basins. Lithologic data and resulting facies patterns were determined largely by use of commercial lithologic logs, supplemented by available surface outcrop data. Well density in the study area is variable, with very sparse control for the Madison and older units in the deeper interior of the basin. Because of the many oil fields in the overlying Pennsylvanian and Permian Minnelusa Formation, many wells have penetrated these beds, but relatively few are drilled into the Madison, and only a small number are drilled through the Madison. About 450 known wildcat wells have been drilled to the top of the Madison within the area of study; of these, about 150 penetrate the entire unit (fig. 3). However, many of these wells were drilled 20 or more years ago and only electric logs and (or) relatively unrefined lithologic logs are available. In many cases, no geologic information other than reported formation tops is available.

Stratigraphic framework

The Madison Limestone is part of a very extensive layer of fossiliferous carbonate rock, Early and Late Mississippian in age (fig. 2).

For this study, the Madison was subdivided into a correlation framework of about 10 or 12 marker-defined units. In general, the marker horizons are better defined to the north in the Williston Basin and the Central Montana Trough, but most of them can be traced with reasonable confidence throughout the area of study (figs. 3, 4, 5, 6, and 7). Figures 8 through 13 are thickness, facies, and porosity layer maps of units bounded by marker-bed horizons.

The Madison and its equivalents occur as a broad, westward-thickening carbonate wedge, ranging from more than 1,500 feet thick in the western Rocky Mountains and Great Basin, and thinning eastward to a north-south zero line in the western Great Plains area. Regionally, the unit is composed mainly of fossiliferous limestone. However, in several broad areas of the eastern Rocky Mountains and western Great Plains, dolomite is a dominant constituent, and in places the Madison is almost entirely dolomite. It is within these areas that maximum porosity is developed, predominantly as intercrystalline matrix porosity within the dolomite facies.

The top of the Madison is a prominent and relatively continuous solution (karst) surface, the result of regional emergence and erosion that occurred shortly after deposition of the carbonate unit. Thus the Madison, where exposed at the surface today, is characterized by many caves, sinkholes, and solution channels, representing a rejuvenation and extension of features originally developed during Late Mississippian and Early Pennsylvanian time. In the subsurface, these features are commonly filled with clay or silt, but more rarely they may occur as open cavities of limited extent.

Porosity calculations

Quantitative porosity calculations were made from all available neutron, sonic, or density logs and converted to porosity-feet[1] for plotting. Only porosity values greater than 10 percent were used in the total porosity-feet compilations, on the assumption that permeability-to-water values in rocks of less than 10 percent porosity would generally be too low to allow substantial water yields. However, these lower porosity dolomites might serve an important water storage and slow-yield function if used as sources for smaller supplies.

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[1] Porosity-feet is percent porosity (expressed as a decimal), taken from a geophysical log, multiplied by the number of feet of strata having this percent porosity. For this study, strata having porosity of less than 10 percent were not used in the calculations.

Stratigraphic facies and porosity patterns

Madison Limestone

The presence of large volumes of ground water in the Madison and its equivalents has been known for several decades, especially since the advent of an active petroleum exploration program in the Rocky Mountains shortly after World War II. The success ratio for petroleum exploration in the Madison reservoir has been small; only a few areas of sizable petroleum accumulation are known, mainly in the Williston Basin, Bighorn Basin, and north-central Montana (fig. 1). No important oil or gas deposits in Madison or pre-Madison rocks have been found in the Powder River Basin. Although the Madison as a petroleum objective has been generally disappointing in most of the Rocky Mountain area, it commonly has shown excellent reservoir quality, often yielding large quantities of water on drill-stem tests.

Overall, the Madison Limestone in the area of study is almost all carbonate rock, with a minor amount of anhydrite which becomes more abundant to the north into the Central Montana Trough and Williston Basin. Dolomite content in general increases to the south and southeast, although in the extreme southern part of the area this trend reverses itself. Within the vicinity of the thinning edge of the Mississippian along the flank of the Transcontinental Arch, the unit is predominantly a fine-grained limestone (micrite). In the northern part of the area, a general increase in percentage of coarser grained limestone occurs in all marker-defined units (figs. 4, 6, 8, 10, and 12). These limestones tend to be composed of either abundant crinoidal remains or oolite banks, commonly in beds distinct from one another but each showing a low degree of dolomitization and porosity development. Adjacent to the east-west crinoidal-oolite facies the rocks change rapidly southward to a belt of relatively coarsely crystalline sucrosic dolomite beds which contain the maximum porosity and permeability development of the section (figs. 6, 9, 11, and 13). Farther south, closer to the Transcontinental Arch, and apparently also within the trough area of the Powder River Basin, the dolomite content continues to increase but becomes much finer grained. At the same time the porosity gradually decreases. These facies relationships result in the interrelated facies-porosity patterns shown in figures 8 to 16.

It should be emphasized that the facies and porosity patterns shown on these maps represent percentage compilations of interbedded lithologic and porosity units. Individual lithologic beds and porosity zones are generally not more than 10-25 feet thick; some may be as much as 50 feet thick, but all tend to be widespread and tabular in overall shape.

From observations thus far, porosity development seems to be related to the position of the coarser crystalline dolomite facies. The finer-grained dolomites to the south of the main porosity-permeability belt show a reasonable degree of porosity, in some cases high, but permeability is probably generally low. Fracture porosity, in terms of total fluid storage, is probably unimportant in most areas of the subsurface, but fracture patterns are important because of their potentially important role of greatly increasing the interconnection between planar beds of porous dolomite and therefore enhancing overall permeability and fluid recovery.

Devonian, Silurian and uppermost Ordovician sequence

For the purposes of this preliminary study, the Devonian, Silurian, and uppermost Ordovician sequence, which thins rapidly southward near the Montana-Wyoming border and across northwestern South Dakota (figs. 6 and 7), was combined into a single unit for porosity analysis (fig. 17). The Devonian and Silurian section thickens and becomes more porous rapidly to the north into the deeper subsurface of the Central Montana Trough and the Williston Basin. East of the Black Hills, however, the porous Devonian beds extend farther south than in eastern Wyoming.

Bighorn Dolomite

The Bighorn Dolomite (equivalent to the Red River Formation of the Williston Basin and Whitewood Dolomite of the Black Hills area) is a fossil-fragmental limestone and crystalline dolomite unit that thins southward from more than 500 feet in east-central Montana and southwestern North Dakota to a sharply-defined east-west pinchout line that extends across the Black Hills, central Powder River Basin, and central Bighorn Mountains (figs. 4 and 18). Generally south of the Wyoming-Montana border, the unit changes from a predominantly fossiliferous limestone facies to a characteristic crystalline sucrosic dolomite facies, a pattern somewhat similar to that of the Madison Limestone units. Similarly, the highly porous sucrosic dolomite belt of the Bighorn unit follows a trend very similar in general aspects to that of the Madison (figs. 4, 6, 18, and 19). Thus, as is the case with the Madison, the maximum porosity development in the Bighorn is directly associated with the occurrence of a more coarsely crystalline sucrosic dolomite facies. Well data indicate, however, that the Bighorn, where present in the deeper parts of the Powder River Basin, may be dominated by a finer crystalline dolomite facies of low porosity. Bighorn porosity geometry (fig. 20), like that of the Madison, tends to be made up of tabular and relatively continuous crystalline dolomite beds, separated by non-porous limestones.

"Winnipeg Sandstone"[2]

The "Winnipeg Sandstone," stratigraphically equivalent to the St. Peter Sandstone of the mid-western United States, is a very clean, generally well-sorted, medium-grained sandstone that in some parts of the northern Powder River Basin and northwestern South Dakota shows good porosity development. The unit pinches out along an east-west line not far from that of the Bighorn Dolomite (figs. 4 and 6). Appraisal and prediction of porosity quality in the "Winnipeg Sandstone" are complicated by the fact that in places the unit is silica-cemented and quartzitic. This is especially true in areas of deeper burial such as within the Powder River Basin, Williston Basin, and Central Montana Trough. For this reason, good porosity is expected in this unit only where it is buried no deeper than a few thousand feet. Prediction of porosity quality in this and other quartzose sandstone units will be aided by combining lithologic and porosity studies with maximum depth-of-burial maps. Because of the silica-cementation mechanism, related to compaction and loading, characteristically affecting a relatively pure quartz sandstone unit such as the "Winnipeg," it seems unlikely that significant porosity will be found in areas of greater than 10-15,000 feet of maximum pre-uplift burial.

Below the Bighorn Dolomite, all important water-bearing units are believed to be sandstones or quartzites. For this report, porosity-feet data for the "Winnipeg Sandstone" are combined with those of the Cambrian Flathead Sandstone, in order to show the distribution of porosity in the two more important lower Paleozoic sandstone units (fig. 21). Some fracture zones may be present in this dominantly clastic rock section, or possibly in Precambrian crystalline rocks. From present indications, however, these are not expected to be of great importance in contributing to the total ground-water resources of the region.

Flathead Sandstone

The Flathead Sandstone is a basal Cambrian unit equivalent to that lying directly above the Precambrian crystalline basement everywhere west and east of the Transcontinental Arch (figs. 2, 4, 5, 6, and 7). This unit is a predominantly quartzose, slightly feldspathic sandstone, commonly cemented with iron oxide. However, like the "Winnipeg Sandstone," it is silica-cemented and quartzitic in many places, especially in areas of deeper burial, so that its porosity quality is good only in shallower depth areas. Figure 21 combines log-calculated porosity-feet data for both the Flathead and "Winnipeg" Sandstones.

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[2] Informal economic name not adopted by U.S.G.S.

Use of the maps

Because better porosity development and the larger porosity-feet values are associated with the coarser crystalline dolomite facies in the Madison and associated carbonate rocks, it is predicted that most wells having the larger yields will be those located in the areas where the carbonate rocks are predominantly coarsely dolomitic. This prognosis is based on available drill-stem-test and flow data from oil and gas test wells, which indicate that large ground-water yields occur where the greatest concentration of coarsely crystalline sucrosic dolomite is present within carbonate units, including the Madison Limestone, Devonian and Silurian carbonates, and the Bighorn Dolomite.

To obtain better subsurface hydrologic information, to test how important dolomitization is in the development of interstitial porosity, to determine if the fracture intensity is lower in a limestone facies, and to properly evaluate areal mapping techniques, two drilling sites were chosen, using the preliminary maps. The first site is in Crook County, northeastern Wyoming, where the area was apparently structurally active, indicating a good potential for secondary fracture porosity. Here the Precambrian rocks are about 4,500 feet deep and potentiometric maps indicate that water from the Madison and older rocks would flow at land surface. Also, preliminary lithofacies and porosity maps show a high percentage of dolomite associated with high porosity in the Madison and other Paleozoic carbonate units. The second site is in Custer County, Montana, where the area was possibly structurally active. Here the Precambrian rocks are about 9,600 feet deep; potentiometric maps indicate that water from the Madison and older rocks would flow at land surface; and the preliminary lithofacies and porosity maps show the Madison and associated rocks are predominantly low porosity limestone. Results indicate that the well drilled at the first site where the Madison and Bighorn carbonates are predominantly coarsely crystalline porous dolomites, has a much larger yield. However, another geologic factor that may contribute to total porosity, and especially permeability, is the structural pattern and attendant fracture porosity. In some parts of the region, structure and paleostructure could have an important effect on yields of wells. For this reason, delineation of fracture belts and paleostructural patterns is currently under way, as is the preparation of lithofacies and porosity maps for the entire 188,000-mi^2 region of the Madison aquifer project. Upon completion of the stratigraphic and structure maps, delineation of areas that are potentially more favorable for wells of larger yields can be made.

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